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Yaejin Moon, MSc, Jacob J. Sosnoff, PhD

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Safe landing strategies during a fall: Systemic review and meta-analysis

Yaejin Moon, MSc, Jacob J. Sosnoff, PhD

Department of Kinesiology and Community Health
University of Illinois at Urbana-Champaign
906 S Goodwin Ave, Urbana, IL 61801

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Correspondence: Yaejin Moon, University of Illinois at Urbana-Champaign, Department of Kinesiology and Community Health, 301 Freer Hall, 906 South Goodwin Ave., Urbana, IL, 61801; Email: ymoon9@illinois.edu; Phone: (217) 244-7006; Fax (217) 244-7322.

Safe landing strategies during a fall: Systemic review and meta-analysis

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;

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. sideway 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.

Methods

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).

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 from1980 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. The search algorithm for each database is provided in Appendix 1. 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.

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].

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 [a]. 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 [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? (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.

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 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.

Fall strategies based on falling directions

Figure 2 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.

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 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 MA rolling technique. All parameters in MA rolling have significant effect sizes ($Ps \leq 0.05$) but effect sizes were not significant for any parameters in MA slapping ($Ps > 0.05$).

Effect of safe falling strategy

Table 2 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 4 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).

Study quality assessment

Table 3 reports results of study quality assessment. Studies included in the review on average scored 13.5 out of 20 and ranged between 8 and18. 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].

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 injures. 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 timecourse 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.

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 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.

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.

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Suppliers

[a]StataCorp, College Station, TX

[b]RevMan 5.3., Cochrane Collaboration, Oxford, UK

Figure 1. Flow chart of study selection *(two column fitting image)*

Figure 2. Schematic representation of safe landing techniques and comparative techniques *(two column fitting image)*

Figure 3. 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. *(two column fitting image)*

Figure 4. Effect sizes (Hedges g) of side-way safe landing strategies. NS = non-significant effect size *(1.5 column fitting image)*

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)

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
[26]Tan (2006) / PP	Backward	Squatting	N=12 (F=9); Age = 27.6+/-10.7 yrs	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
[13]Robinovitch (2004) / PP	Backward	Squatting	N=23 (F=23); Age = 24+/-5 yrs	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
[20]Chou (2001) / PP	Forward	Elbow Flexion	N=11(F=0); Age=26.1+/-2.6 yrs	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.
[23]Lo (2003) / RCT	Forward	Elbow Flexion	N=29(F=0); Age=23+/-3 yrs	Expected tether release in standing position	Wrist; Neck/Impact force; Impact velocity	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;
[25]Robinovitch (2003) / PP	Side	Forward/ Backward Rotation	N=22(F=22); Age=23+/-5 yrs	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.
[22]Groen (2007) / PP	Side	Martial arts fall (Rolling & Slapping)	N=11(F=0); Age=24.2+/-3.8 yrs	Self-initiated fall in kneeling position	Hip/Impact force; Impact velocity; Impact angle	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.

Note: PP=Pre-post study; randomized control trial, RCT;

(Table 1 continued)

Author(year)/ study design	Fall direction	Safe landing strategy	Subjects	Fall simulation method	Impact part / severity parameter	Fall strategy instructions
[19]van der Zijden (2012) / PP	Side	Martial arts fall	N=12(F=3); Age=27.6+/-10.7 yrs	Self-initiated fall in kneeling position	Hip/Impact force; Impact angle	Followed method of Groen 2007
[24]Groen (2008) / PP	Side	Martial arts fall (Rolling & Slapping)	N=5(F=0); Age=23.8+/-4.1 yrs	Self-initiated fall in kneeling position	Hip/ Impact force; Impact velocity	Followed method of Groen 2007
[11]Weerdesteyn (2008) / PP	Side	Martial arts fall (Rolling & Slapping)	N=10(F=10); Age=28.3+/-6.6 yrs	Self-initiated fall in kneeling position	Wrist/Impact force	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.
[15]Groen (2010) / PP	Side	Martial arts fall (Rolling & Slapping)	N=25(F=19); Age=69.5+/-5.9 yrs	Self-initiated fall in kneeling position	Hip/Impact force; Impact velocity; Fall duration	Followed method of Groen 2007
[18]Sabick (1999) / PP	Side	Relaxed muscle, Slap	N=9(F=2); Age=NR	Self-initiated fall in kneeling position	Hip/Impact force; Impact velocity	The subject was told to fall with his body "as relaxed as possible". Also the participants were instructed to perform a slap fall
[21]Van den Kroonenberg (1996) / PP	Side	Relaxed muscle	N=6(F=NR); Age=23.7+/-3.67 yrs	Self-initiated fall in standing position	Hip/Impact velocity; Impact angle	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.
[16]Feldman (2007) / Cohort	Side	Stepping	N=44(F=31); Age=21+/-2 yrs	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: PP=Pre-post study; randomized control trial, RCT;

Table 2. Quantitative effect of protective strategies

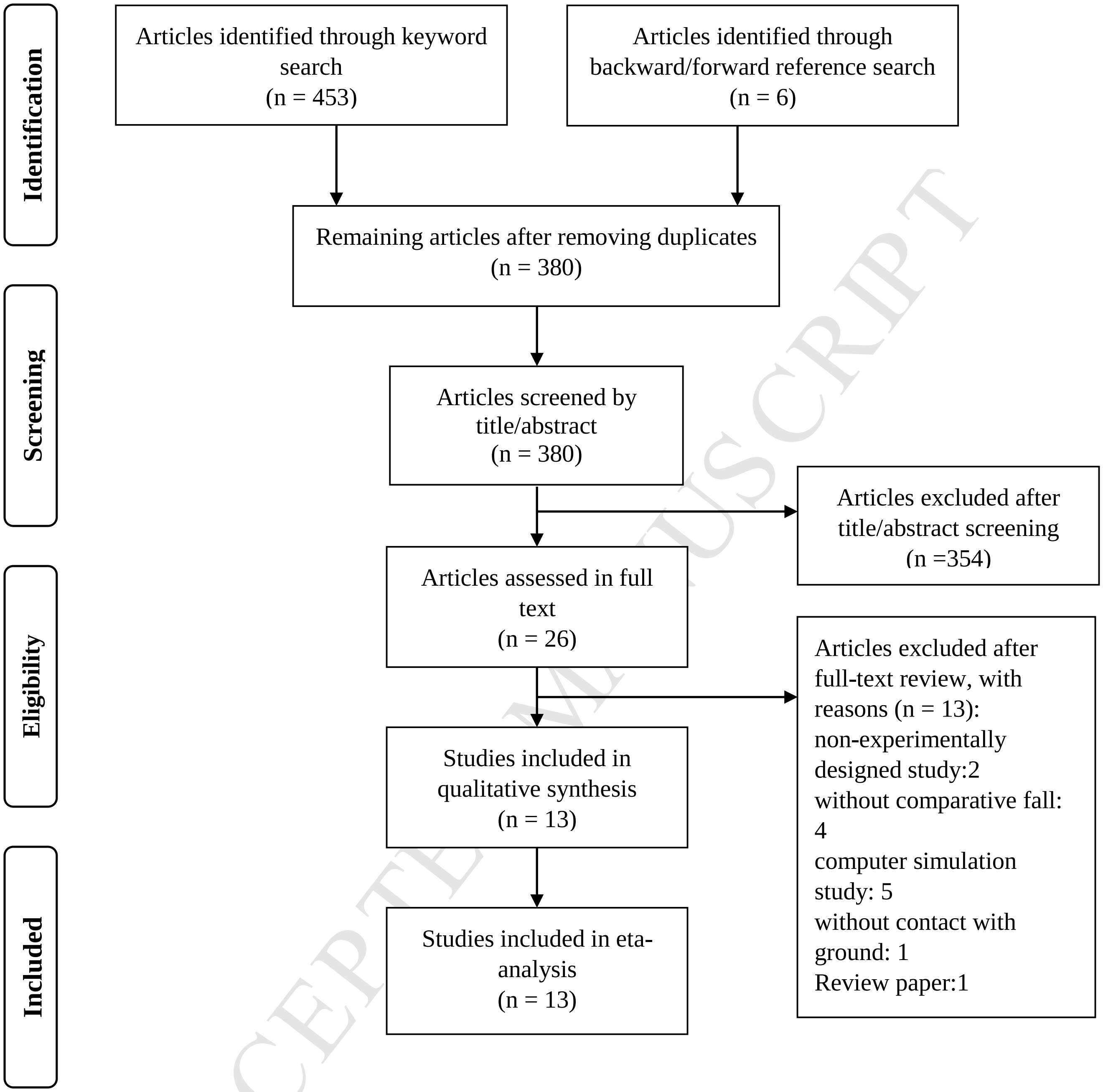
Fall direction	Safe landing strategy	Impact part	Severity parameter	Statistical result
Backward	**Squatting** vs no-squatting	Wrist	Impact velocity	**Significantly ↓ (2.27+/-0.30 m/s to 2.01+/-0.13 m/s)**
			Fall duration	**Significantly ↓ (873+/-67 ms to 749+/-72 ms)**
		Hip	Impact velocity	**Significantly ↓ (3.3+/-0.3 m/s to 2.7 +/- 0.3 m/s)**
			Impact Energy	**Significantly ↓ (307+/-90 J to 172+/-56 J)**
Forward	**Elbow flexion** vs Elbow extension when catching the ground	Hand	Impact force	**Significantly ↓ (880+/-40 N to 745+/-42N)**
		Wrist	Impact force	**Significantly ↓ (11.2+/-3.6 N/kg.g 8.2+/-3.4 N/kg.g)**
			Impact velocity	**Significantly ↓ (2.66+/-0.21 m/s to 2.52+/-0.15 m/s)**
		Elbow	Impact force	**Significantly ↓ (10.3+/-6.5 N/kg.g to 6.2+/- 11 N/kg.g)**
		Shoulder	Impact force	**Significantly ↓ (32.6 +/-6.5 N/kg.g to 24.1 +/- 11 N/kg.g)**
		Neck	Impact velocity	Not significantly different (2.69+/-0.25m/s vs 2.68+/-0.24m/s)
Side	**Forward rotation** vs backward rotation	Hip	Impact velocity	**Significantly ↓ in forward rotation (2.95 +/- 0.25 m/s to 2.45 +/- 0.77 m/s)**
			Impact Energy	**Significantly ↓ in forward rotation (238 +/- 70 J to 156 +/- 90 J)**
	MA Rolling vs blocking fall	Hip	Fall duration	Not significantly different (246+/-92 ms vs 235 +/-72ms)
			Impact force	**Significantly ↓ in 5 out of 5 papers (Values are provided at Fig 3)**
			Impact velocity	**Significantly ↓ in 3 out of 4 papers (Values are provided at Fig 3)**
			Impact angle	**Significantly less vertical in 2 out of 2 papers (Values are provided at Fig 3)**
	MA Slapping vs no-slap when performing Martial arts fall	Hip	Impact force	Not significantly different in 2 out of 3 papers (Values are provided at Fig 3)
			Impact velocity	Not significantly different in 2 out of 2 papers (Values are provided at Fig 3)
			Impact angle	Not significantly different (17+/-5 degree vs 15+/-4 degree)
	Relaxed muscle vs Stiffed muscle	Hip	Impact force	Not significantly different (2.76+/-0.83 N/kg.g and 2.69+/-0.68 N/kg.g)
			Impact velocity	**Significantly ↓ (3.31 +/- 0.43 m/s to 3.09 +/- 0.41m/s)**
			Impact angle	**Significantly less vertical (13.6 +/- 11.2 degree to 21.8 +/-10.4 degree)**
	Stepping vs non-stepping before falling	Hip	Fall duration	**Significantly ↑ (613 +/- 53 ms to 691 +/- 46 ms)**
			Impact velocity	**Significantly ↓(3.16 +/- 0.74 to 2.46 +/- 0.94 m/s)**

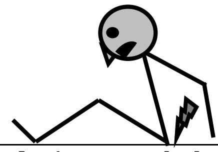
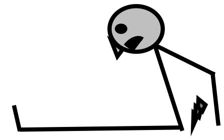
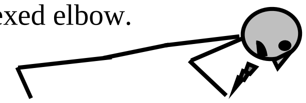
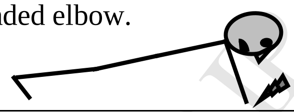
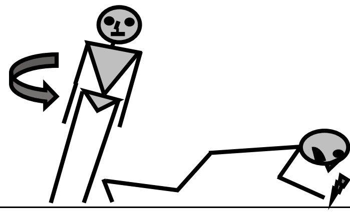
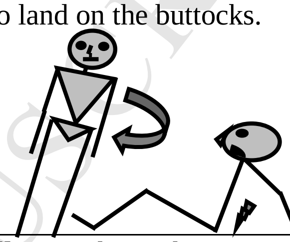
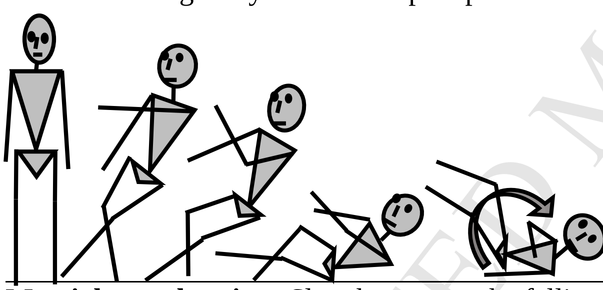
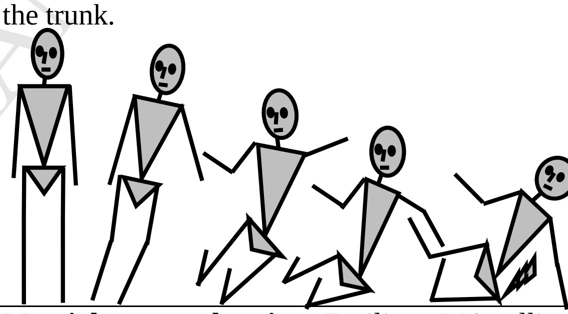
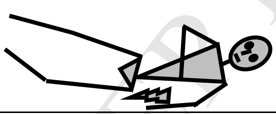
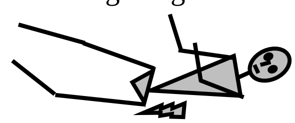
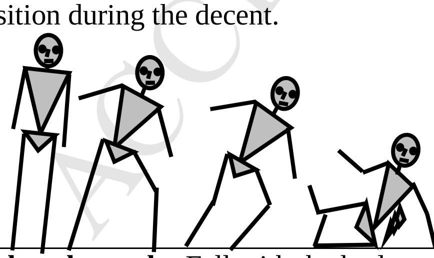
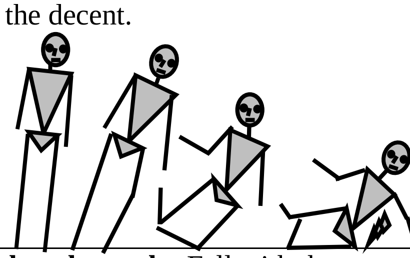
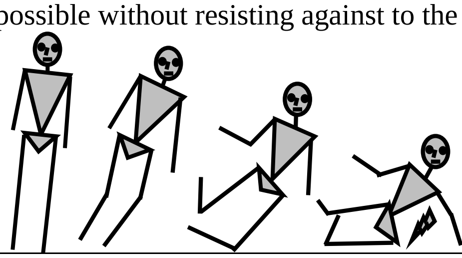
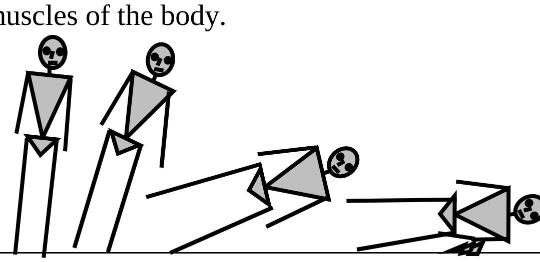
Note: MA=martial arts; ↓=reduced; ↑=increased

Table 3. Study quality assessment

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

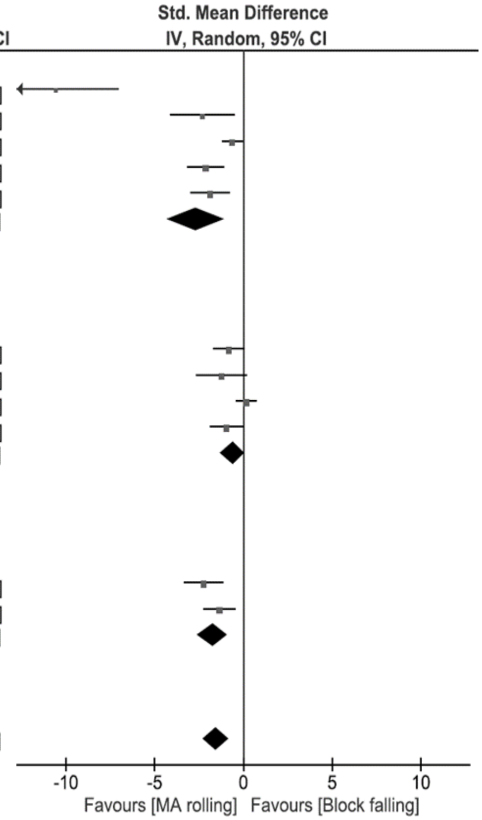
Notes: Scores for each criterion range from 0 to 2, depending on whether the criterion was unmentioned or unmet (0), partially met (1), or completely met (2). The total study score ranges between 0 and 20.


Identification
Screening
Eligibility
Included
Articles identified through keyword search (n = 453)
Articles identified through backward/forward reference search (n = 6)
Remaining articles after removing duplicates (n = 380)
Articles screened by title/abstract (n = 380)
Articles excluded after title/abstract screening (n =354)
Articles assessed in full text (n = 26)
Articles excluded after full-text review, with reasons (n = 13):
non-experimentally designed study:2
without comparative fall: 4
computer simulation study: 5
without contact with ground: 1
Review paper:1
Studies included in qualitative synthesis (n = 13)
Studies included in eta-analysis (n = 13)

Fall direction	Safe landing technique	Comparative technique
Backward	**Squatting:** Flex the knees and hips while contracting the muscles spanning these joints. 	**No squatting:** Fall backward with the extended knee. 
Forward	**Elbow Flexion:** Catch the ground with the outstretched arms while landing with the slightly flexed elbow. 	**Elbow extension:** Catch the ground with outstretched arms while landing with the extended elbow. 
Side	**Forward Rotation:** Rotate forward during the descent to land on the outstretched hands. 	**Backward Rotation** Rotate backward during the descent to land on the buttocks. 
	Martial arts rolling: Flex knee during the decent, flex trunk laterally and rotate slightly backward to facilitate rolling away from the impact point. 	**Block fall:** Stretch out the arm into the direction of the impending the fall while laterally flexing the trunk. 
	Martial arts slapping: Slap the arm on the falling side on the ground after the impact of MA rolling. 	**Martial arts no slapping:** Facilitate MA rolling without contacting the ground with the arms 
	Stepping: Reposition the foot in a more lateral position during the decent. 	**No stepping:** Stay the foot in the same position during the decent. 
	Relaxed muscle: Fall with the body as relaxed as possible without resisting against to the fall 	**Non-relaxed muscle:** Fall with the tensed muscles of the body. 

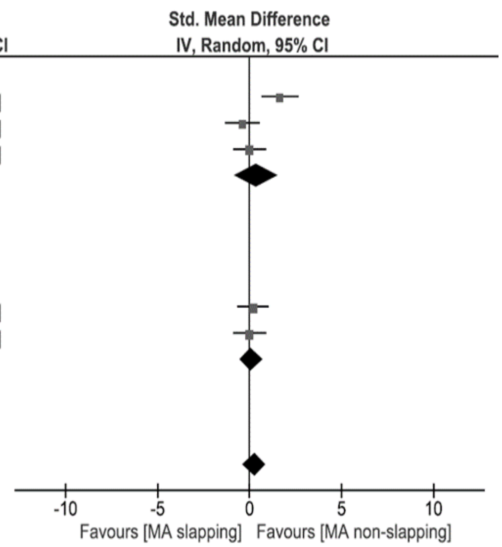
(a) MA rolling vs Block falling

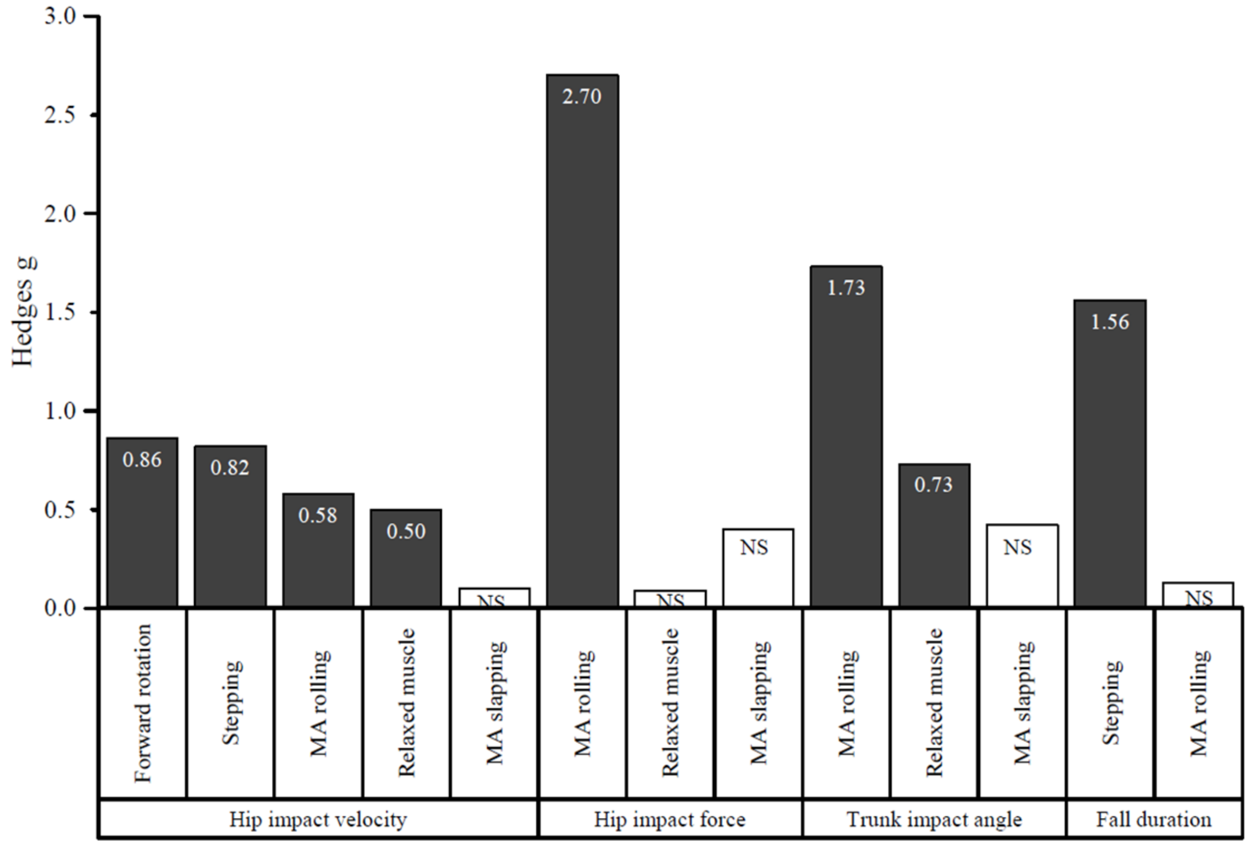
Study or Subgroup	MA rolling Mean	SD	Total	Block falling Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.1.1 Hip impact force (N/kg.g)								
Groen 2007	2.8	0.1	11	3.9	0.1	11	3.1%	-10.58 [-14.13, -7.03]
Groen 2008	2.97	0.48	5	4.14	0.43	5	7.0%	-2.32 [-4.12, -0.52]
Groen 2010	2.26	0.35	25	2.46	0.26	25	11.2%	-0.64 [-1.21, -0.07]
van der Zijden 2012	2.4	0.4	12	3.4	0.5	12	9.7%	-2.13 [-3.17, -1.10]
Weerdesteyn 2008	2.1	0.2	10	2.6	0.3	10	9.5%	-1.88 [-2.97, -0.79]
Subtotal (95% CI)			**63**			**63**	**40.5%**	**-2.70 [-4.31, -1.09]**
Heterogeneity: Tau² = 2.69; Chi² = 36.17, df = 4 (P < 0.00001); I² = 89%								
Test for overall effect: Z = 3.29 (P = 0.001)								
1.1.2 Hip impact velocity (m/s)								
Groen 2007	1.23	0.2	11	1.4	0.2	11	10.3%	-0.82 [-1.69, 0.06]
Groen 2008	1.22	0.1	5	1.37	0.12	5	8.3%	-1.23 [-2.65, 0.19]
Groen 2010	1.26	0.22	25	1.22	0.26	25	11.3%	0.16 [-0.39, 0.72]
Weerdesteyn 2008	1	0.2	10	1.2	0.2	10	10.1%	-0.96 [-1.89, -0.02]
Subtotal (95% CI)			**51**			**51**	**39.9%**	**-0.58 [-1.28, 0.12]**
Heterogeneity: Tau² = 0.29; Chi² = 7.45, df = 3 (P = 0.06); I² = 60%								
Test for overall effect: Z = 1.63 (P = 0.05)								
1.1.3 Trunk impact angle (degrees)								
Groen 2007	72	3	11	79	3	11	9.4%	-2.24 [-3.36, -1.13]
van der Zijden 2012	71	16	12	87	3	12	10.2%	-1.34 [-2.24, -0.44]
Subtotal (95% CI)			**23**			**23**	**19.6%**	**-1.73 [-2.61, -0.86]**
Heterogeneity: Tau² = 0.14; Chi² = 1.53, df = 1 (P = 0.22); I² = 35%								
Test for overall effect: Z = 3.87 (P = 0.0001)								
Total (95% CI)			**137**			**137**	**100.0%**	**-1.56 [-2.30, -0.83]**
Heterogeneity: Tau² = 1.16; Chi² = 61.03, df = 10 (P < 0.00001); I² = 84%								
Test for overall effect: Z = 4.18 (P < 0.0001)								
Test for subgroup differences: Chi² = 7.77, df = 2 (P = 0.02), I² = 74.2%								



(b) MA slapping vs MA non-slapping

Study or Subgroup	MA Slapping Mean	SD	Total	MA non-slapping Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.2.1 Hip Impact force (N/kg.g)								
Groen 2007	2.87	0.1	11	2.7	0.1	11	18.5%	1.64 [0.64, 2.63]
Sabick 1999	2.44	0.7	9	2.76	0.83	9	19.4%	-0.40 [-1.33, 0.54]
Weerdesteyn 2008	2.1	0.2	10	2.1	0.2	10	20.5%	0.00 [-0.88, 0.88]
Subtotal (95% CI)			**30**			**30**	**58.4%**	**0.40 [-0.78, 1.57]**
Heterogeneity: Tau² = 0.85; Chi² = 9.52, df = 2 (P = 0.009); I² = 79%								
Test for overall effect: Z = 0.66 (P = 0.51)								
1.2.2 Hip impact velocity (m/s)								
Groen 2007	1.23	0.2	11	1.19	0.2	11	21.2%	0.19 [-0.65, 1.03]
Weerdesteyn 2008	1	0.2	10	1	0.2	10	20.5%	0.00 [-0.88, 0.88]
Subtotal (95% CI)			**21**			**21**	**41.6%**	**0.10 [-0.51, 0.71]**
Heterogeneity: Tau² = 0.00; Chi² = 0.10, df = 1 (P = 0.76); I² = 0%								
Test for overall effect: Z = 0.33 (P = 0.75)								
Total (95% CI)			**51**			**51**	**100.0%**	**0.27 [-0.37, 0.90]**
Heterogeneity: Tau² = 0.32; Chi² = 9.98, df = 4 (P = 0.04); I² = 60%								
Test for overall effect: Z = 0.82 (P = 0.41)								
Test for subgroup differences: Chi² = 0.20, df = 1 (P = 0.66), I² = 0%								

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MA rolling
Relaxed muscle
MA slapping
MA rolling
Relaxed muscle
MA slapping
MA rolling
Relaxed muscle
MA slapping
Stepping
MA rolling
Hip impact velocity
Hip impact force
Trunk impact angle
Fall duration