Journal of Biomechanics 83 (2019) 291–297

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Preliminary investigation of teaching older adults the tuck-and-roll strategy: Can older adults learn to fall with reduced impact severity

Yaejin Moon *, Alka Bishnoi, Ruopeng Sun, Jong Cheol Shin, Jacob J. Sosnoff

Department of Kinesiology and Community Health, University of Illinois at Urbana-Champaign, Urbana, IL, United States

ARTICLE INFO

Article history:
Accepted 3 December 2018

Keywords:
Falls
Movement
Training
Impact
Injury

ABSTRACT

Falls are common and potentially disastrous for older adults. A novel approach that could augment current fall prevention procedures is to teach older adults movement strategies to reduce the risk of injury. The purpose of the study was to determine whether older adults can learn a movement strategy ("tuck-and-roll") that reduces fall impact severity. Learning was quantified with short-term acquisition, bilateral transfer and 1-week-retention. 14 healthy older individuals participated (63.9 ± 5.6 years) in the investigation. Participants were randomly assigned into either training group (n = 7) or active control group (n = 7). All participants performed standardized sideway falls at baseline, immediately post intervention and 1-week-retention tests. During the falling assessments, kinetic and kinematic impact severity parameters were measured. The results for short-term learning revealed that the training group showed greater reduction in hip impact force (33% reduction) than the control group (16% reduction). Furthermore, there was partial bilateral transfer effect and 1-week retention observed in the training group. The observations provide preliminary evidence that teaching tuck-and-roll strategy to older adults has potential effect. The observations provide preliminary evidence that older adults might reduce impact severity utilizing tuck-and-roll strategy during unpredictably-timed sideway falls.

1. Introduction

Falls are one of the leading causes of accidental injury and death among the elderly (Centers for Disease Control and Prevention, 2014). 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 (Stel et al., 2004). 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 (Centers for Disease Control and Prevention, 2013). Indeed, 90% of hip fractures and 80% of hospital admissions for traumatic brain injury in older adults result from falls (Parkkari et al., 1999; Harvey and Close, 2012). Falls not only lead to physical injuries but they also lead to activity curtailment, physiological deconditioning and reduction in quality of life in older adults (Stevens et al., 2006). Given the frequency and severity of falls, insights are necessary to decrease the risk of injury from falls.

Decades of research has demonstrated that fall incidence can be reduced with targeted interventions (Chang et al., 2004). However, even in individuals who participate in evidence-based fall prevention programs, falls are still common and disastrous (Chang et al., 2004). Consequently, even in best case scenarios older adults are at risk for a fall-related injury.

An alternative approach that may augment current fall prevention practices is instructing older adults to fall in such a way that they reduce their risk of injury. Biomechanical based research has demonstrated that training of safe landing strategies (i.e. movement patterns) can significantly reduce loads applied to the body at impact (i.e. impact severity) (Weerdesteyn et al., 2008). A systematic review reported that seven safe landing strategies have been reported in 13 investigations encompassing 217 participants (Moon and Sosnoff, 2017). Overall, it was found that the tuck-and-roll strategy was the most effective strategy to reduce impact severity and reduced hip impact force by 28%.

Despite great promise, the review also revealed several limitations. Perhaps the largest limitation was that the research to date has almost exclusively focused on healthy young adults (Groen et al., 2007). Only one study (Groen et al., 2010) included elderly subjects and suggested that elderly participants were able to learn tuck & roll technique and reduced hip impact force. However, the study utilized self-initiated falls from a kneeling position, which may not accurately reflect real-life falls (Lord et al., 2007). Lastly, the research has simply demonstrated short-term changes in

* Corresponding author.
E-mail address: ymoon9@illinois.edu (Y. Moon).

https://doi.org/10.1016/j.jbiomech.2018.12.002
0021-9290/

motor performance (i.e. changes in impact biomechanics immediately following training) and not examined retention. Consequently, there is a dearth of information concerning older adult's ability to learn safe-falling strategies and whether these strategies reduce fall-related injury risk.

Motor learning is classically defined as a change in the capability to perform a skill that must be inferred from a relatively permanent improvement in performance as a result of practice (Magill and Anderson, 2007). Best practices indicate that to quantify motor learning, several characters need to be demonstrated: (1) improvement in performance of the motor skill (i.e. acquisition); (2) ability to adapt the motor skill to different settings (i.e. transfer) and; (3) retain improvements in motor performance over a period without practice (i.e. retention). Although there is abundant data to suggest that baseline motor skills performance is reduced in older adults, the ability to learn (i.e. acquire, transfer and retain) new motor skills remains relatively intact in old age (Voelcker-Rehage, 2008; Seidler, 2007; Smith et al., 2005).

Since the greatest risk of hip fractures occurs in side-way falls (Parkkari et al., 1999), the current investigation focused on instructing a sideway fall technique. Consistent with the principles of motor learning, learning was quantified with changes in impact load following training, bilateral transfer of the falling strategy to the untrained side and with 1-week retention effect. We hypothesized that the training group who learned the tuck-and-roll technique would exhibit greater reduction in impact severity than the active control group who were simply exposed to falling trials without receiving instruction. Also, we hypothesized that there would be no difference in impact severity measurements between the right and the left side falling – indicating bilateral transfer. Lastly, we hypothesized that the impact severity parameters measured at one-week follow-up assessment would not differ from that at the post-assessment – indicating retention.

2. Method

The investigation was unblinded pilot randomized control trial examining the impact of tuck-and-roll strategy instruction on fall impact parameters in older adults (NCT# 0017577). All procedures for the investigation were approved by the local institutional review board.

2.1. Participants

Older adults who resided in the local community were recruited through advertisements. Inclusion criteria were designed to include healthy seniors who are capable of safely undergoing the procedures. The inclusion criteria included being between the ages of 55–75 years, weighing between 45 and 100 kg, and being between 150 and 195 cm tall, minimal fracture risk, adequate muscle strength and cognitive function. To minimize the risk of injury, participants had to have adequate bone mass density (t-score > −1.0). Adequate muscle strength was defined as being able to complete 5 times sit-to-stand test within 10 s. Also, to ensure that the participants have the cognitive ability to understand instruction and learn a new skill, we included individuals scoring Montreal Cognitive Assessment (MoCA) over 26. Additionally, to ensure that the tuck-and-roll strategy was a novel motor skill, we recruited individuals without experience of learning the tuck-and-roll strategy (e.g., martial arts, gymnastics, parachuting training). Lastly, to have the main training on their dominant side, we included individuals being right-handed.

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

2.2. Sample size

We used a relevant study to compute the sample size needed for detecting a difference of impact loads between the pre (untrained falling strategy) and post (trained the tuck-and-roll strategy) trials. Groen et al. (2010) observed the safe landing training in older adults decreased normalized hip impact force from 2.46 (N/kg/g) to 2.26 (N/kg/g) with effect size (cohen's *d*) of 1.00. Thus, we estimated that a sample size of 7 subjects in the training group would provide 80% power at the 5% level of significance.

2.3. Study design

Fig. 1 provides a schematic of the experimental procedures. Enrolled participants attended a total of three sessions over two weeks. The first visit included initial screening assessment. During the initial screening, bone mineral density measurements were performed with DEXA bone densitometers (Hologic QDR 4500, Hologic Inc, Waltham, MA). Also, the 5-times sit-to-stand and MoCA tests were conducted. After the initial screening assessment, the study participants who satisfied the inclusion/exclusion criteria were randomized to one of two arms (1) the training group or (2) an active control group (repeated falling with their natural response). The participants were randomly assigned into the two groups using a simple randomization method with 1:1 allocation ratio by computer-generated random numbers. Following randomization, the participants underwent a series of 6 falls (3 right and left-side falls) as a baseline assessment ($T0_{baseline}$). After completion of baseline testing, the training group received 30 min of introductory training on the tuck-and-roll strategy to learn basics of the strategy. The training was progressive and standardized (Appendix A). The active control group was not administered training.

The participants returned 2 days following baseline assessment. During the second visit, an intermediate assessment was conducted prior to the practice (T1). Then, the training group received 60 min of training on right-side falling. It focused on learning to apply the tuck-and-roll strategy in the falling experimental setup (see 2.4.) for 9 trials. After each trial, the training group received feedback on their performance. The active control group was also exposed to 9 falling trials but did not receive instruction or feedback on their performance. After the intervention, participants in both groups completed a post assessment (T2). Their third visit occurred 1 week later for a 1-week retention test ($T3_{retention}$).

2.4. Falling experimental setup and protocol

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

During the experiments, participants were made to fall sideways onto a 20 cm crash pad by releasing an inextensible tether that supports the participants at a 10° lean from vertical (Fig. 2). This angle is based on previous research to represent values that exceed the capacity of participants to recover from falling by taking a single step (Hsiao and Robinovitch, 2001). The 10° initial lean angle was obtained by adjusting the length of the tether, so the selected reading was observed from a goniometer. The tether

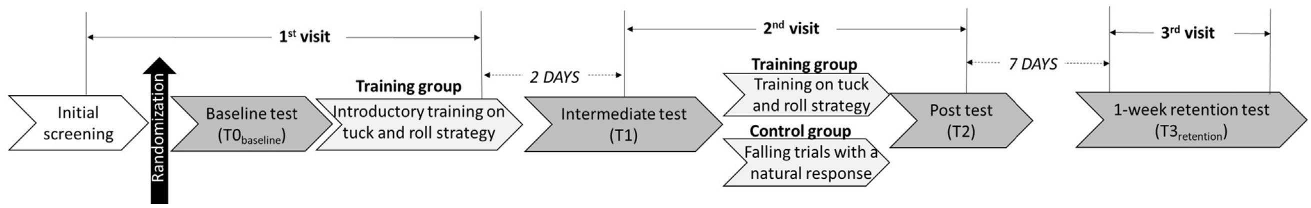

Fig. 1. Experimental procedures.

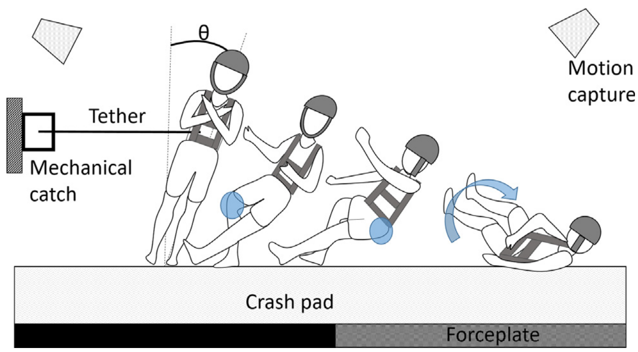

Fig. 2. Experimental setup of a falling simulation.

was released via a mechanical catch (a snap shackle). The fall was unpredictably-timed by randomly assigning a time delay between 3 and 8 s. The order of presentations of the right and left falls was randomized between participants in all assessments. Prior to tether release, the participants were instructed to look forward at eyelevel, and kept the hips and knees extended with their arm crossed over their chest. Music was played to minimize aural cues of release of the mechanical catch. In the assessment, the participant was instructed to "land on the mat in a way that feels comfortable for you". Additionally, since hip fracture risk was the main interest of the current study, it was emphasized to land on the hip first by restraining from landing on the hand first, taking a step or kneeling. Hip was defined as a projection of the pelvis and greater trochanter on each side of the body (Robinovitch et al., 2003). All tests consisted of 6 falling trials (3 right and left-side falls).

2.5. Data collection and analyzes

As primary effect of the tuck-and-roll strategy is reducing hip fracture risk (Moon and Sosnoff, 2017), hip impact force and hip impact velocity were analyzed (Fig. 3(a and b)). We also quantified head acceleration (Fig. 3(c)) as a measure of risk of head injury. Considering that head injury is a significant result of falls, quantifying its risk was important to provide an evidence of clinical significance of the strategy.

Forceplate (S-Mill, Motekforce Link, Amsterdam, Netherlands) was utilized to estimate impact force applied on the hip during a fall. The force data were recorded by the CueFors2 software (Motekforce Link, Amsterdam, the Netherlands) at 500 Hz. Hip impact force was determined as the maximum force in the vertical direction at hip impact, normalized for body weight. The data were analyzed using custom routines (MATLAB, MathWorks, Natick, MA).

Additionally, a ten-camera motion capture system (VICON, Oxford Metrics, Oxford, England) was used to collect kinematic data of the hip and the head. Six reflective markers were attached bilaterally on the hip (anterior iliac spine, posterior iliac spine and greater trochanter). Five reflective markers were attached on the anterior, bilateral and posterior head gear. The motion capture system tracked the 3D coordinates of the reflective markers at a sample rate of 100 Hz. To maximize accuracy, a representative marker was selected in each segment since some markers were occluded at impact (Appendix B). Then, a VICON Nexus software (VICON, Oxford Metrics, Oxford, England) calculated velocity data of the representative marker. Using a custom MATLAB script, the velocity data were low-pass-filtered with a fourth-order Butterworth filter with a cutoff frequency of 10 Hz (Groen et al., 2010). Then, head acceleration was computed by numerical differentiation of the head velocity and subsequently low-pass-filtered with a fourth-order Butterworth filter with a cutoff frequency of 20 Hz (Groen et al., 2010). Maximum head acceleration was calculated as a maximum value of head vertical acceleration. We neglected horizontal components of the parameters since it has been shown that they were 10-fold smaller than vertical components and they have relatively little effect on risk of injury during a fall (Robinovitch et al., 2004).

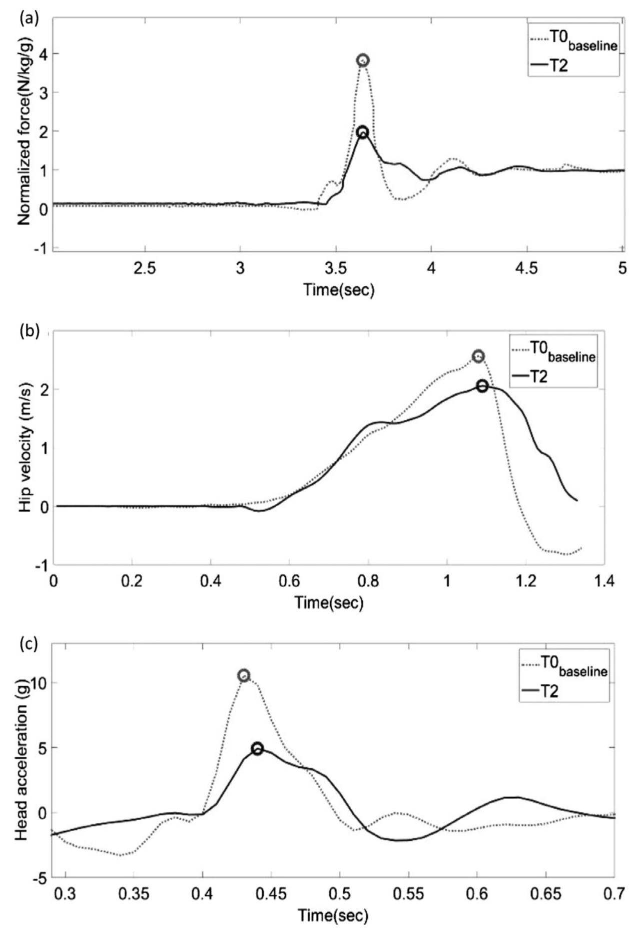

Fig. 3. Impact severity parameters–time profile of a representative participant during a single trial of a sideway fall of baseline and post-assessment. (a) normalized force (b) hip velocity (c) head acceleration.

The performance of each trial was also recorded with a video camera to analyze whether the participants landed on the hip first (Appendix C) and to probe frequency of head impact (supplementary material S1).

The relative ratio (RR) of impact load between baseline-test and post-test ($RR = \frac{post\ test}{baseline\ test} \times 100\%$) served as a primary indicator of motor learning. RR less than 100% indicates reduction in impact severity at post-test while RR greater than 100% indicates an increase. This normalization procedure for impact severity parameters is beneficial in that it controls for possible confounds in the statistical results because of the baseline difference (Hinder et al., 2011). Descriptive statistics for raw impact severity parameters are reported in supplementary material (S2).

2.6. Statistical analysis

Statistical analysis was performed using SPSS for Windows, version 19.0 (IBM, Inc., Chicago, IL). Participant demographics were compared between the groups with independent t-tests. To test the first hypothesis (short-term acquisition), repeated-measures analysis of variance (repeated-measures ANOVA) was performed with time ($T0_{baseline}$, T1, T2) as within-participant factor and group (training, control) as between participant factors for each impact severity parameter. To test the second hypothesis (transfer), repeated-measures ANOVA was conducted impact severity parameters with falling-side (right, left) as within-participant factor and group (training, control) as between-participant factors. To test the third hypothesis (retention), repeated-measures ANOVA was conducted on impact severity parameters with time (T2, $T3_{retention}$) as within-participant factor and group (training, control) as between participant factors. Measure of eta-squared (η^2) was obtained as the effect size for repeated-measures ANOVA analysis. For all repeated-measure ANOVA tests, normality of residuals was tested using Shapiro-Wilk test and sphericity was tested with Mauchly's test. It was confirmed that none of the tests violated these assumptions. All analyses used two-sided tests, and *p* values equal or less than 0.05 were considered statistically significant.

3. Results

3.1. Participant flow

Participant flow through recruitment and enrollment is outlined in Fig. 4. A total of 37 of individuals who met inclusion criteria were assessed for eligibility. After screening, a total of 17 participants were deemed eligible and randomly assigned to the training or control group. After the initial session, three participants (2 males, 1 female) discontinued the study due to mild

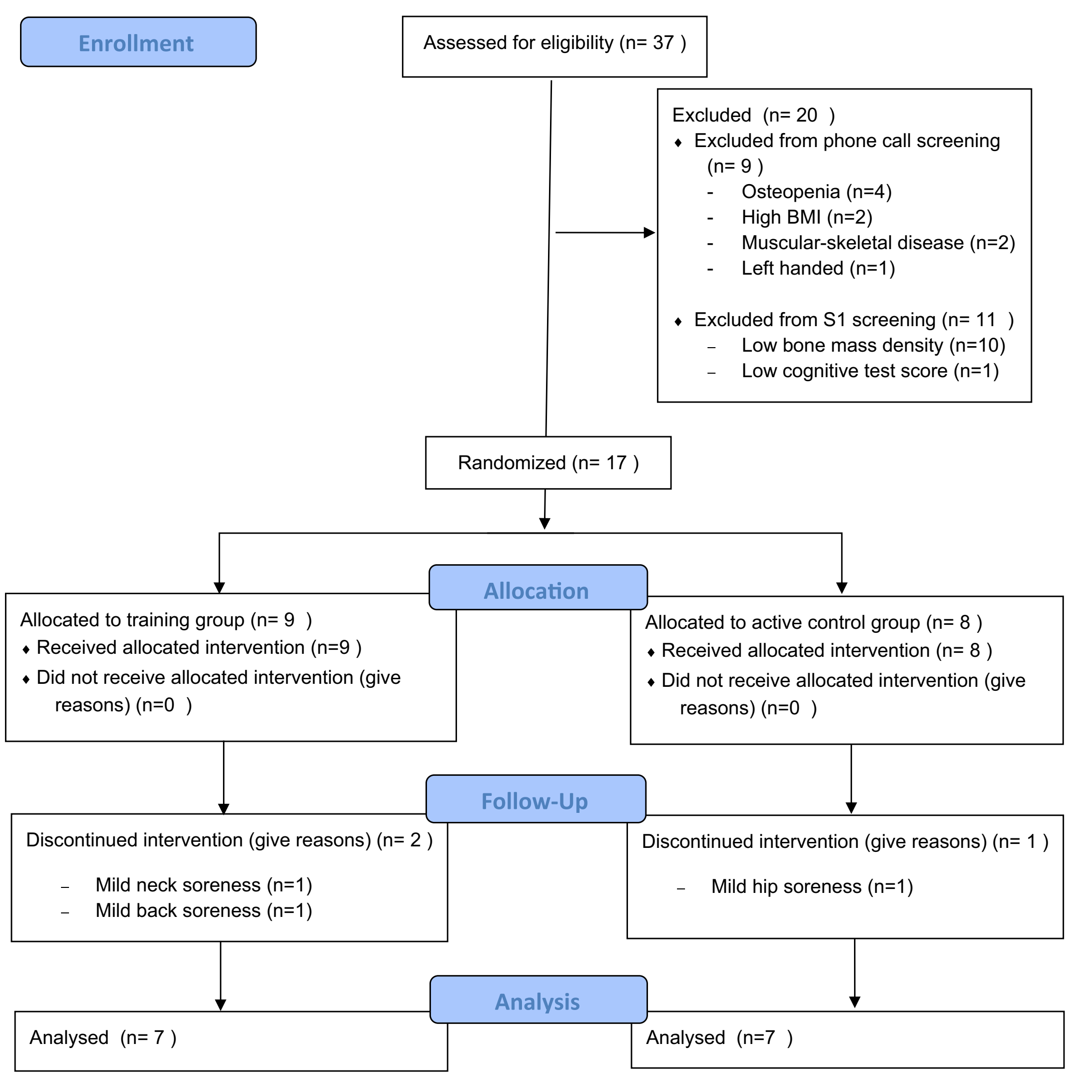

Fig. 4. Participant flow diagram.

muscle soreness. A total of 14 participants completed the study (n = 7 training; n = 7 control).

3.2. Participant characteristics

A comparison of training and control group characteristics are reported in Table 1. The average age of the participants was 63.9 ± 5.6 years. Ten of the 14 participants (72%) were male. All participants in the both groups performed above cutoff scores of 5 times sit to stand and MoCA tests, although the training group performed significantly better in 5 times sit to stand ($t(12) = -3.89$, $p < 0.01$) and MoCA ($t(12) = -3.86$, $p = 0.01$). Overall, this performance indicates that the sample consisted of healthy older adults. There were no significant correlations between 5-times sit-to-stand nor MoCA and any of the impact severity parameters (p's > 0.05).

3.3. Baseline assessment

Overall, normalized hip impact force ranged from 2.03 (N/kg/g) to 4.55 (N/kg/g) with an average of 3.23 ± 0.74 (N/kg/g). Maximum head acceleration ranged from 2.67 (g) to 17.4 (g) with an average of 5.37 ± 3.81 (g). Hip impact velocity ranged from 1.49 (m/s) to 3.47 (m/s) with an average of 2.52 ± 0.10 (m/s).

3.4. Short-term training effect on impact severity measurements

Fig. 5 demonstrates impact severity measurements as a function of group and time. It is clear in the figure that there is a reduction in normalized hip impact force and maximum head acceleration as a function of time and that the reduction is greatest in the training group. However, there was no significant group × time effect on hip impact velocity. Statistical analyses (Table 2) confirm these observations. Specifically, the training group reduced hip impact force by 33% while the control group reduced 16%. Also, there was 54% reduction in maximum head acceleration in the training group while there was no significant change in the control group.

3.5. Bilateral transfer effect

Fig. 6 illustrates impact severity measures as a function of side and group at T2. Overall, there was no difference in impact severity between sides in normalized hip impact force$_{(RR)}$ and hip impact velocity$_{(RR)}$ (*p's* > 0.05) indicating both sides of falls showed similar rate of reduction in hip impact severity. However, there was greater maximum head acceleration$_{(RR)}$ ($F_{(1,12)} = 5.72$, $p = 0.02$, $\eta^2 = 0.32$) in the left-side fall compared to the right-side fall. There was no side × group interaction effect in all of the impact severity parameters (*p's* > 0.05) in both T2 and T3$_{retention}$. These observations indicate there was bilateral transfer in reducing impact severity of hip but not of the head in the both groups.

Table 1
Participant demographics.

	Training	Control	p-value
N	7 (2F/5 M)	7 (2F/5 M)	–
Age (yrs)	64.3 ± 4.4	63.5 ± 6.6	0.79
Height (cm)	171.9 ± 5.7	169.6 ± 8.0	0.55
Weight (kg)	71.3 ± 10.5	69.7 ± 11.9	0.80
BMI (kg/m^2)	24.0 ± 3.4	24.4 ± 5.2	0.87
Bone Mass Density (t-score)	−0.42 ± 0.84	0.00 ± 0.92	0.43
5 times sit to stand (sec)	6.07 ± 1.01	7.99 ± 0.83	*<0.01
MoCA	29.7 ± 0.5	27.9 ± 1.5	*0.01

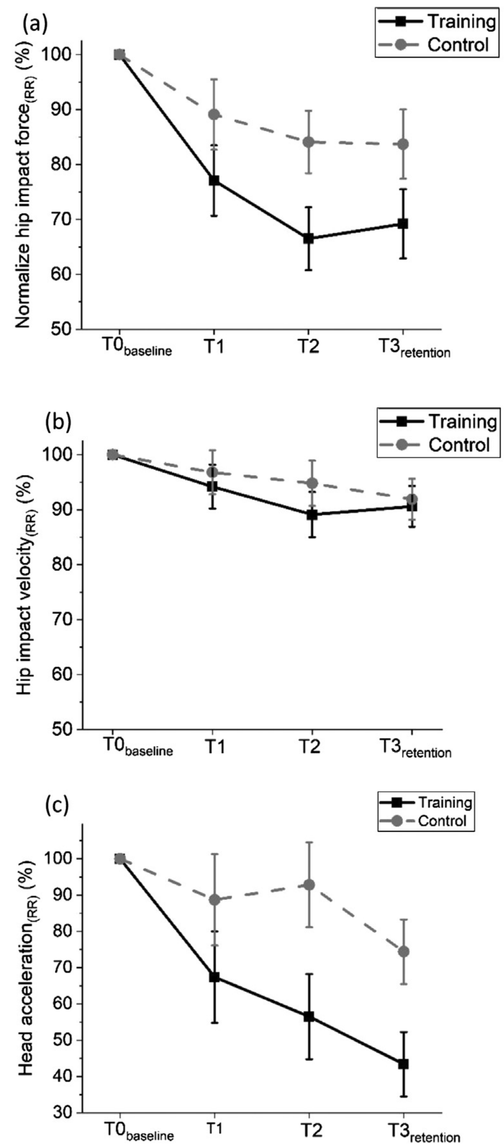

Fig. 5. Impact severity measurements as a function of group × time of (a) normalized hip impact force$_{(RR)}$ (b) hip impact velocity$_{(RR)}$ (c) maximum head acceleration$_{(RR)}$.

3.6. 1-week retention effect

Statistical analysis revealed there was no significant time (T2, T3$_{retention}$) effect nor group × time effect in hip impact severity (*p's* > 0.05). However, there was a significant reduction in maximum head acceleration$_{(RR)}$ ($F_{(1,11)} = 6.56$, $p = 0.01$, $\eta^2 = 0.35$) at T3$_{retention}$. Overall, the results indicate that there was similar or even greater rate of reduction in impact severity in the retention test compare to T2 implying that the both groups demonstrated retention over a 1-week time period.

4. Discussion

The purpose of this investigation was to determine if it is possible to instruct older adults in movement strategies that reduce impact severity during sideway falls. A total of 14 healthy older individuals (7 training and 7 control) completed the study. The novel observation was that the training group learned the tuck-and-roll strategy which resulted in 33% reduction in hip impact

Table 2
Statistical results of short-term learning test.

Impact parameters	Group	T1	T2	Time effect	Group × time effect
Normalized hip impact force$_{(RR)}$	Training	77.1 ± 6.4(%)	66.5 ± 5.7(%)	$F_{(2,24)} = 22.5$, $p < 0.01$, $\eta^2 = 0.65$	$F_{(2, 24)} = 2.86$, $p = 0.04$, $\eta^2 = 0.19$
	Control	89.1 ± 6.4(%)	84.1 ± 5.7(%)		
Hip impact velocity$_{(RR)}$	Training	94.2 ± 4.0(%)	89.1 ± 4.1(%)	$F_{(2,24)} = 5.12$, $p = 0.01$, $\eta^2 = 0.84$	$F_{(2, 24)} = 0.97$, $p = 0.20$, $\eta^2 = 0.49$
	Control	96.8 ± 4.0(%)	94.8 ± 4.1(%)		
Maximum Head acceleration$_{(RR)}$	Training	67.4 ± 12.6(%)	56.5 ± 11.7(%)	$F_{(2,24)} = 6.09$, $p < 0.01$, $\eta^2 = 0.34$	$F_{(2, 24)} = 2.68$, $p = 0.04$, $\eta^2 = 0.18$
	Control	88.7 ± 12.6(%)	92.8 ± 11.7(%)		

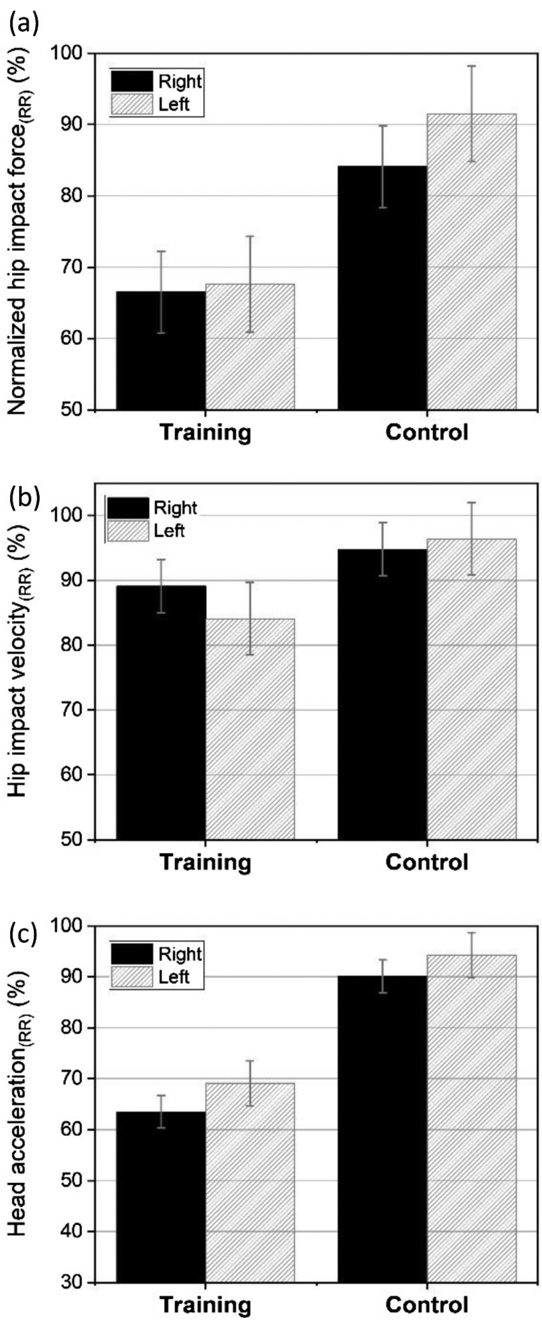

Fig. 6. Impact severity parameters at T2 as a function of falling-side × group. (a) normalize hip impact force$_{(RR)}$ (b) hip impact velocity$_{(RR)}$ (c) maximum head acceleration$_{(RR)}$.

force and 59% reduction in maximum head acceleration following training. Furthermore, there was evidence of skill transfer and retention over a 1 week observed in the training group.

Consistent with the hypothesis, training of the tuck-and-roll strategy resulted in a decrease in hip impact force (33% reduction) and head acceleration (54% reduction). It is important to note that the improvement in fall severity in the training group was twice that of the control group, indicating that improvements were above simple fall exposure.

It has previously been proposed that the tuck-and-roll technique reduce impact severity by reducing the amount of energy dissipation at impact due to distribution of the impact force applied to the body part along the contact path while rolling (Weerdesteyn et al., 2008). Consistent with this view it has been reported that rolling results in a higher kinetic energy of the body after impact, which results in a smaller amount of kinetic energy transformed into strain energy at impact (Groen et al., 2008).

The ability of the older individuals in the training group to reduce their impact force by utilizing the tuck-and-roll strategy corroborates the result of the previous studies with young adults (Moon and Sosnoff, 2017). However, it should be also noted that the previous studies of young adults observed improved performance after only 30 min of training (Weerdesteyn et al., 2008), whereas the current study provided 90 min of training over two sessions. The optimal amount of training necessary for older adults to learn the tuck-and-roll strategy is not clear. Given that the rate of learning is slower in older adults (Voelcker-Rehage and Willimczik, 2006), it is likely that they will require more training than young adults.

In partial agreement to our hypothesis, the training group exhibited complete bilateral transfer in reducing hip impact force, whereas the head acceleration was considerably greater in the untrained falling direction (left) compared to the trained falling direction (right). We postulate that the observed deficiency of bilateral transfer in head acceleration is resulted from incomplete learning of the head control during a fall. To maximize clearance between the head and the ground for head protection, the participants in the training group were instructed to tuck the chin while performing tuck-and-roll. However, a qualitative evaluation of tuck-and-roll performance (supplementary material S3) revealed that chin-tuck component of the skill was infrequently performed. Therefore, it is possible that if sufficient training was provided, participants might have learned the head control thoroughly and exhibited improved bilateral transfer.

Consistent with our hypothesis, the participants in the training group exhibited 1-week retention. This reflects the previous notion that long-term memory in aging is preserved and intact despite age-associated declines in motor speed and central dopaminergic functions (Smith et al., 2005). Furthermore, results of head acceleration and qualitative evaluation demonstrated that the head control further improved at 1-week follow-up ($T3_{retention}$) compared to the short-term acquisition test (T2). These findings potentially reflect offline learning - characterized by enhancement of a motor skill through the passage of time without additional practice (Siengsukon and Boyd, 2009). To exploit these findings for the benefit of training efficiency, practice schedule should be designed to ensure enough temporal spacing between the training sessions.

Another important observation is that the active control group also had significant reduction in hip impact force over time. Although the amount of reduction was less than that of the training group, the 16% reduction in hip impact force in the control group was significant. We attribute this to the phenomenon of "implicit learning" where individuals teach themselves a movement (Magill, 1998). Implicit learning has been observed in perturbation training where older adults were able to improve stepping strategies to recover balance when simply exposed to repeated external perturbations without instruction (Pai et al., 2014).

It is promising that this novel movement-centric approach might be a beneficial addition to currently developed methods to reduce hip impact force. Specifically, it has been reported that hip impact force could be attenuated by 20.2% with hip protectors when falling speed is between 2 m/s and 3 m/s (Laing et al., 2011) and up to 34% with compliant flooring (Glinka et al., 2013). However, those approaches have issues such as poor compliance (hip protectors) and spatial limitations (compliant flooring). Training tuck-and-roll strategy does not have those issues and might serve as a complementary method to reduce injury risk from a fall.

However, it should be also noted that the tuck-and-roll strategy most likely is only suitable for a certain segment of the older adult community. It is logical to speculate that a person will need adequate muscle strength and reaction time to properly perform the strategy (Moon and Sosnoff, 2017). Other inherent issues with teaching older adults to fall safely is injury risk and need for qualified instructors. Further investigation is necessary to determine safe training procedure for older adults.

There is a number of limitations in this study. A major limitation of the study is the small sample size. However, as a pilot study, the current investigation would inform power calculation for future research (Appendix C). Another limitation of the study is unique characteristics of the participants (e.g. healthy older adults, mainly male participants) which compromises generalizability of the results. Additionally, research examining the potential benefits of this training approach in more at risk populations is warranted. A further limitation is that as in any laboratory study including postural perturbations, questions exist regarding how accurately the experiments simulate real-life falls. Although the "tether-release" method has been utilized in a number of experimental paradigms (Robinovitch et al., 2003), this method has no initial velocity unlike an actual trip or slip during walking (Hsiao-Wecksler, 2008). Second, while our participants did not know the exact time of release, they knew that a fall was about to happen, and this allowed them to pre-plan their falling strategy. Third, it is possible that participants may have been less fearful of falling on to a soft mat than onto a rigid surface. Further research is needed to examine the applicability of the tuck-and-roll technique in a more real-life like experimental setting. Lastly, the duration for intervention (90 min) and for follow-up assessment (1-week) was relatively short to provide data concerning long-term benefits of the training.

Despite decades of research demonstrating that fall incidence can be reduced with targeted-intervention, fall-related death rate has increased over the last fifteen years (Centers for Disease Control and Prevention, 2014b). This novel movement-centric approach to enhance safe landing responses represents a potential addition to currently developed tools to reduce fall related injury. Although the development of such programs for general older population will be challenging, the current investigation serves as a starting point.

Conflicts of interest

The authors have no conflict of interest.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2018.12.002.

References

Centers for disease control and prevention, C. 2013. Ten Leading Causes of non-fatal Injury (Charts) [Online]. Available: http://www.cdc.gov/injury/wisqars/LeadingCauses.html 2015].

Centers for disease control and prevention, C. 2014a. Ten Leading causes of Death (Charts) [Online]. Available: http://webappa.cdc.gov/sasweb/ncipc/mortrate10_us.html [Accessed 02/01/2016.

Centers for disease control and prevention, C. 2014b. Unintentional fall death rates, Adults 65+. Atlanta, GA.

Chang, J.T., Morton, S.C., Rubenstein, L.Z., Mojica, W.A., Maglione, M., Suttorp, M.J., Roth, E.A., Shekelle, P.G., 2004. Interventions for the prevention of falls in older adults: systematic review and meta-analysis of randomised clinical trials. BMJ 328, 680.

Glinka, M.N., Cheema, K.P., Robinovitch, S.N., Laing, A.C., 2013. Quantification of the trade-off between force attenuation and balance impairment in the design of compliant safety floors. J. Appl. Biomech. 29, 563–572.

Groen, B.E., Smulders, E., de Kam, D., Duysens, J., Weerdesteyn, V., 2010. Martial arts fall training to prevent hip fractures in the elderly. Osteoporos. Int. 21, 215–221.

Groen, B.E., Weerdesteyn, V., Duysens, J., 2007. Martial arts fall techniques decrease the impact forces at the hip during sideways falling. J. Biomech. 40, 458–462.

Groen, B.E., Weerdesteyn, V., Duysens, J., 2008. The relation between hip impact velocity and hip impact force differs between sideways fall techniques. J. Electromyogr. Kinesiol. 18, 228–234.

Harvey, L.A., Close, J.C.T., 2012. Traumatic brain injury in older adults: characteristics, causes and consequences. Injury 43, 1821–1826.

Hinder, M.R., Schmidt, M.W., Garry, M.I., Carroll, T.J., Summers, J.J., 2011. Absence of cross-limb transfer of performance gains following ballistic motor practice in older adults. J. Appl. Physiol. 110, 166–175.

Hsiao-Wecksler, E.T., 2008. Biomechanical and age-related differences in balance recovery using the tether-release method. J. Electromyogr. Kinesiol. 18, 179–187.

Hsiao, E.T., Robinovitch, S.N., 2001. Elderly subjects' ability to recover balance with a single backward step associates with body configuration at step contact. J. Gerontol. Ser. A: Biol. Sci. Med. Sci. 56, M42–M47.

Laing, A.C., Feldman, F., Jalili, M., Tsai, C.M., Robinovitch, S.N., 2011. The effects of pad geometry and material properties on the biomechanical effectiveness of 26 commercially available hip protectors. J. Biomech. 44, 2627–2635.

Lord, S.R., Sherrington, C., Menz, H.B., Close, J.C., 2007. Falls in older people: risk factors and strategies for prevention. Cambridge University Press.

Magill, R.A., 1998. Knowledge is more than we can talk about: Implicit learning in motor skill acquisition. Res. Q. Exerc. Sport 69, 104–110.

Magill, R.A., Anderson, D., 2007. Motor learning and control: Concepts and applications. McGraw-Hill, New York.

Moon, Y., Sosnoff, J.J., 2017. Safe landing strategies during a fall: Systematic review and meta-analysis. Arch. Phys. Med. Rehabil. 98, 783–794.

Pai, Y.C., Bhatt, T., Yang, F., Wang, E., 2014. Perturbation training can reduce community-dwelling older adults' annual fall risk: A randomized controlled trial. J. Gerontol. A Biol. Sci. Med. Sci. 69, 1586–1594.

Parkkari, J., Kannus, P., Palvanen, M., Natri, A., Vainio, J., Aho, H., Vuori, I., Jarvinen, M., 1999. 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. 65, 183–187.

Robinovitch, S.N., Brumer, R., Maurer, J., 2004. Effect of the "squat protective response" on impact velocity during backward falls. J. Biomech. 37, 1329–1337.

Robinovitch, S.N., Inkster, L., Maurer, J., Warnick, B., 2003. Strategies for avoiding hip impact during sideways falls. J. Bone Miner. Res. 18, 1267–1273.

Seidler, R.D., 2007. Aging affects motor learning but not savings at transfer of learning. Learn. Mem. 14, 17–21.

Siengsukon, C.F., Boyd, L.A., 2009. Does sleep promote motor learning? Implications for physical rehabilitation. Phys. Ther. 89, 370–383.

Smith, C.D., Walton, A., Loveland, A.D., Umberger, G.H., Kryscio, R.J., Gash, D.M., 2005. Memories that last in old age: motor skill learning and memory preservation. Neurobiol. Aging 26, 883–890.

Stel, V.S., Smit, J.H., Pluijm, S.M.F., Lips, P., 2004. Consequences of falling in older men and women and risk factors for health service use and functional decline. Age Ageing 33, 58–65.

Stevens, J.A., Corso, P.S., Finkelstein, E.A., Miller, T.R., 2006. The costs of fatal and non-fatal falls among older adults. Inj. Prev. 12, 290–295.

Voelcker-Rehage, C., 2008. Motor-skill learning in older adults—a review of studies on age-related differences. Eur. Rev. Aging Phys. Activity 5, 5–16.

Voelcker-Rehage, C., Willimczik, K., 2006. Motor plasticity in a juggling task in older adults-a developmental study. Age Ageing 35, 422–427.

Weerdesteyn, V., Groen, B.E., van Swigchem, R., Duysens, J., 2008. Martial arts fall techniques reduce hip impact forces in naive subjects after a brief period of training. J Electromyogr. Kinesiol. 18, 235–242.