ELSEVIER

Journal of Biomechanics 40 (2007) 2612–2618

JOURNAL
OF
BIOMECHANICS

www.elsevier.com/locate/jbiomech
www.JBiomech.com

Reducing hip fracture risk during sideways falls: Evidence in young adults of the protective effects of impact to the hands and stepping

Fabio Feldman, Stephen N. Robinovitch*

Injury Prevention and Mobility Laboratory, School of Kinesiology, Simon Fraser University, Burnaby, BC, Canada

Accepted 23 January 2007

Abstract

Hip fracture is rare in young adults, despite evidence that the energy available in a fall is sufficient to fracture the young proximal femur. This might be explained by protective responses that allow young individuals to avoid hip impact during sideways falls. To test this hypothesis, we conducted experiments with 44 individuals (31 women and 13 men) aged 19–26 years, who were instructed to try to maintain balance after a sudden unpredictable sideways translation was applied to the platform they stood upon. While the surface adjacent to the platform was formed of gymnasium mats, we provided no information on surface compliance, or the direction and speed of the perturbation. Ninety percent of participants fell and impacted the pelvis, and 98% of those cases involved direct impact to the hip region. Impact occurred to the hand in 98% of falls, and preceded impact to the pelvis by 50 ms on average (SD = 40, range = −12–175 ms). The impact velocity of the pelvis decreased 3.6% for every 10 ms increase in the interval between hand and pelvis impact, and was reduced by 22% on average by stepping prior to impact. Our results suggest that the lack of hip fractures in young adults cannot be explained by avoidance of hip impact during sideways falls. Rather, it probably relates to use of the hands and stepping, and by simply possessing sufficient bone strength to withstand the direct blow to the greater trochanter that tends to accompany sideways falls.

Keywords: Falls; Balance; Hip fracture; Wrist fracture; Osteoporosis; Impact biomechanics; Protective responses

1. Introduction

There are over 25,000 annual hip fractures among the elderly in Canada, and over 90% of hip fractures are due to falls (Grisso et al., 1991). However, unlike fall-related wrist fractures (which are common throughout the lifespan), hip fracture is a relatively rare event in young adults, even among athletes who regularly experience sideways falls. This is surprising, since the energy available during a fall ranges from 100 to 300 J (Robinovitch et al., 2004), while only about 25 J are required to fracture the proximal femur of young adults (Courtney et al., 1995).

One possible factor to explain the low occurrence of hip fractures in the young relates to the mechanics of the fall. Risk for hip fracture in the elderly is six times greater during sideways than forward or backward falls, and 30 times greater if the fall results in direct impact to the hip region (Nevitt and Cummings, 1993). Conversely, impacting one or both hands decreases fracture risk 3-fold (Greenspan et al., 1994; Schwartz et al., 1998). Therefore, young adults might be protected against hip fracture during a sideways fall by the tendency to avoid impact to the hip, or the tendency to impact the hands and/or knees.

Anecdotal support for this notion includes the high frequency of fall related wrist fractures in young adults (Owen et al., 1982), which suggests that hand impact is common, and results from several studies showing there is sufficient time during descent for individuals to move their hand(s) into a protective position and activate upper extremity muscles to break a fall (DeGoede et al., 2001; Kim and Ashton-Miller, 2003; Robinovitch et al., 2005; Dietz and Noth, 1978).

More direct support is provided by the results of Hsiao and Robinovitch (1998), who found that during unexpected sideways falls initiated by sudden translation of the

---

*Corresponding author. Tel.: +1 604 291 3566; fax: +1 604 291 3040.
E-mail address: stever@sfu.ca (S.N. Robinovitch).

0021-9290/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.jbiomech.2007.01.019

support surface, young adults tended to avoid hip impact by rotating their trunk forward during descent to land on both outstretched hands. Unfortunately, this study involved a small sample size ($n = 6$) and a small number of sideways falls ($n = 13$). Furthermore, since each participant underwent multiple trials, the results may have reflected a learning effect.

Conflicting results were reported by van den Kroonenberg et al. (1996), who found that most of their young adult participants did not impact the ground with the outstretched hand during self-initiated sideways falls, despite being instructed to do so. In their study, hip impact tended to occur before contact of the arm or hand. Sabick et al. (1999) also reported this tendency of the arm to strike the ground after hip impact. A problem with these studies was the self-initiated nature of the falls, which allowed for preplanning of a landing strategy, unlike unexpected falls in daily life.

Given the conflicting nature of this evidence, our goal in the current study was to determine whether unexpected sideways falls in young adults elicit a common sequence of protective responses that are known to protect against hip fracture. We focused specifically on the following questions: (1) what is the frequency of impact to the lateral aspect of the hip during unexpected sideways falls in young adults? and (2) what is the frequency of impact to the upper extremity and knees during such falls? We addressed these questions through a novel experimental paradigm, which challenged participants to try to maintain balance after experiencing a sudden unpredictable perturbation, and in the vast majority of cases elicited a sideways fall.

2. Materials and methods

2.1. Participants

The participants in our falling experiments consisted of 44 young individuals (31 women and 13 men) ranging in age from 19 to 26 years (mean age = 21 years (SD = 2)), body mass from 43 to 112 kg (mean mass = 65 kg (SD = 14)), and body height from 149 to 187 cm (mean height = 168 cm (SD = 9)). All participants were undergraduate students enrolled in a biomechanics course who volunteered to participate in an experimental "balance competition." Participants were healthy and free of diagnosed neurological disease or debilitating orthopedic conditions, and 87% of them participated at least twice a week in some type of physical activity. All participants provided written informed consent, and the experimental protocol was approved by the Research Ethics Committee of Simon Fraser University.

2.2. Experimental protocol

During the balance test, the participant stood barefoot on top of a rubber sheet that, without warning, was made to translate horizontally to the participant's right side (Fig. 1a) by means of a linear motor (T4D motor, Trilogy System Corporation, Webster, Texas, USA). As shown in Fig. 1b, the total displacement was set to 1.15 m (actual mean value = 1.14 m, SD = 0.04), the terminal velocity was set to 2.2 m/s (actual peak value = 2.22 m/s, SD = 0.07), and the initial acceleration and terminal deceleration was set to 30 m/s^2 (actual mean value = 29.2 m/s^2, SD = 2.0).

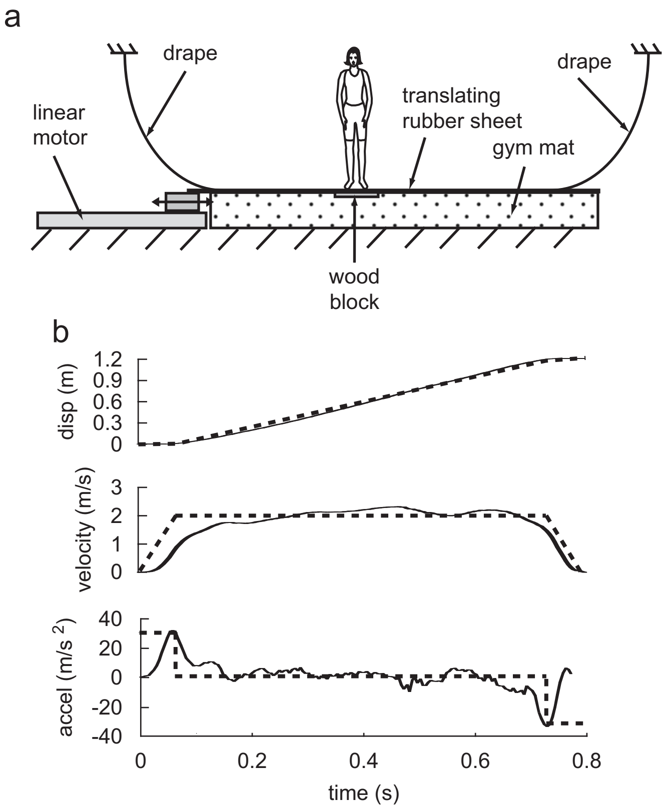

Fig. 1. Experimental setup and motion profile for falling experiments. (a) During the experiment, the participant stood upon a rigid platform mounted flush to surrounding gymnasium mats, which were concealed under a rubber sheet. Drapes were placed on both sides of the room to prevent the participant from guessing the nature of the perturbation. (b) A linear motor was used to translate the rubber sheet suddenly to the right, initiating imbalance (dashed lines = reference command profile; solid lines = actual movement profile from a typical trial, measured from reflective markers on the rubber sheet).

We used several precautions to minimize participants' ability to preplan a postural response, in order to mimic a real-life fall. The only instruction we provided to the participant was: "your balance will be perturbed, and your goal is to maintain your balance." Moreover, the room was completely masked to prevent the participant from anticipating what was to come. The participant was guided to stand on a rigid platform mounted flush to the gymnasium mat landing surface, and the entire surface was masked with the rubber sheet. Drapes were used to conceal the linear motor and related hardware. No information was provided about the compliance of the ground surface, or the nature of the perturbation. In order to focus on naive responses, each participant performed only one trial, and no practice trials were allowed. Furthermore, all testing was completed in a single afternoon, and participants who were waiting to be tested were prevented from having contact with those who completed the testing.

Immediately following the experiment, we conducted a structured interview with each participant, which included the question "right before the trial, while you were standing on top of the platform, were you aware that the floor was going to move before it did?" Only 10% of participants responded "yes" to this question, and 90% responded "no." Thus, few participants interpreted the statement "your balance will be perturbed" to mean that the floor would move from under them. While we did not inquire about alternative expectations, these may have included expectations that they would be nudged from behind, or would be asked to perform movements that challenged their balance to gradually increasing degrees (such as standing or hopping on one leg, or reaching as far as possible, etc.).

We used an eight-camera, 240 Hz motion measurement system (Motion Analysis Inc., CA, USA) to acquire three-dimensional positions of 18 reflective, skin-surface markers located at the head, sacrum (L5/S1 junction), and bilaterally at the acromion process (shoulder), lateral epicondyle of the humerus (elbow), distal end of the radius (hand), anterior–superior–iliac spine (ASIS), greater trochanter (hip), lateral epicondyle of the femur (knee), lateral malleolus (ankle), and third metatarsal (toe). As a safety measure, participants wore helmets and wrist guards (over which the head and hand markers were secured). Three markers were also placed on the translating rubber sheet overlying the impact surface.

2.3. *Data analysis*

For each trial, we inspected motion data to determine whether or not a fall occurred, whether a step was executed in an attempt to recover balance, the sequence of impacting body parts, and the orientation of the pelvis at the time of impact. A participant was considered to have fallen if any body part other than the feet contacted the impact surface. We 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. We classified a trial as involving a "partial step", if there was lifting and swinging of the left leg in the lateral direction, or the right leg in the medial direction, but impact to a hand, knee, or the pelvis before that foot was repositioned on the ground. Finally, we classified a trial as "no attempt to step" if there was no apparent attempt to lift and swing the left foot laterally, or the right leg medially. Hand and hip impact times were determined by the frame in which the hand or pelvis marker (ASIS, sacral, or hip) crossed a virtual line located 5 cm above the mean vertical position of the three markers located on the impact surface. The hip proximity angle (α) reflects how close the individual came to directly impacting the lateral aspect of the pelvis (or greater trochanter of the proximal femur), with $\alpha = 0$ deg indicating direct impact to the lateral aspect of the pelvis, and $\pm 90^\circ$ indicating impact to the buttocks or anterior aspect of the pelvis (Fig. 2a). Anatomical considerations suggest that values of α greater than 30° will produce direct loading to the ischium (for backward rotation) or ilium (for forward rotation). Therefore, an α value less than 30° was regarded as indicating hip impact (Fig. 2b). Pelvis impact velocity was calculated as the vertical velocity of the left hip marker at the instant of pelvis impact.

2.4. *Statistical analysis*

Our primary research questions were addressed descriptively by examining the frequency and temporal sequence of impact to the hip, knees, and hands. We conducted secondary analysis using independent sample *t*-tests to determine whether specific protective responses (use of a step, or impacting the hand before the hip) affected pelvis impact velocity (an indication of fall severity). We also used Pearson correlations to examine associations between continuous variables. We regarded $p < 0.05$ to indicate significant effects. All statistical tests were conducted with statistical analysis software (SPSS Inc., version 12.0, Chicago, IL, USA).

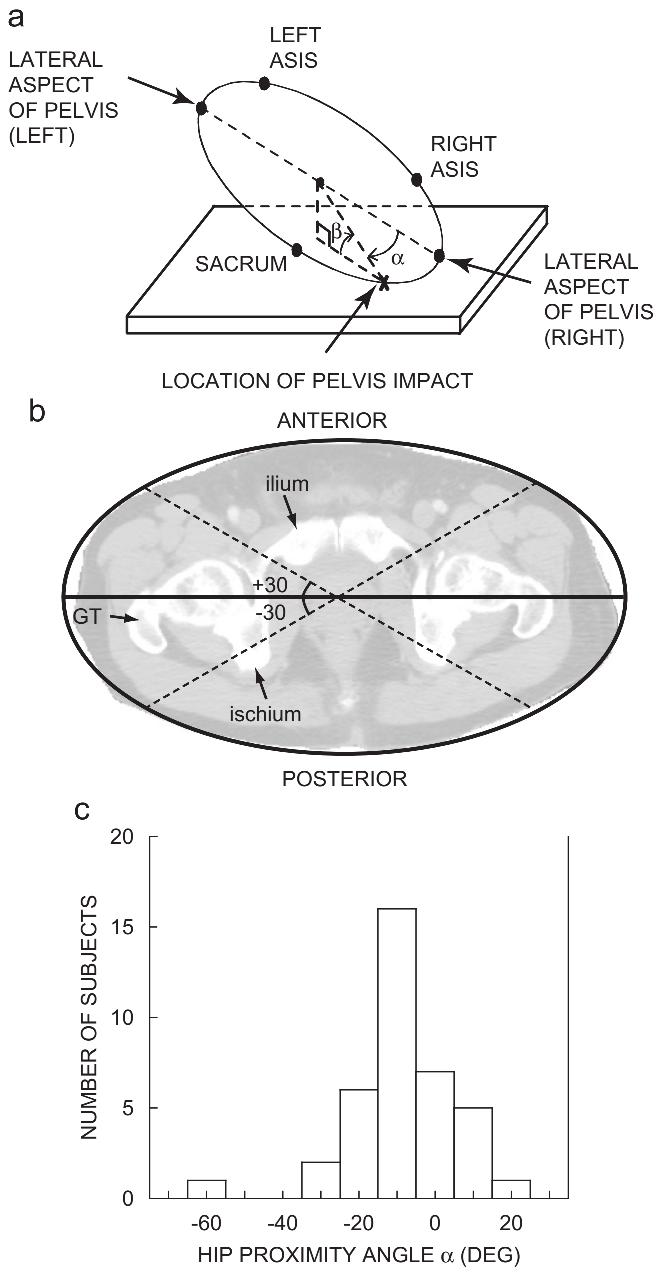

Fig. 2. (a) The hip proximity angle (α) reflected how near the point of impact was to the lateral aspect of the pelvis. To calculate α, we first identified an ellipse whose circumference passed through the sacrum, right ASIS, and left ASIS markers. The lateral aspects of the pelvis were assumed to coincide with the endpoints of the major axis of this ellipse. We then identified the site of pelvis impact as the lowest point on the circumference of this ellipse, at the time of impact. Finally, we defined α as the angle between the site of pelvis impact and the nearest lateral aspect of the pelvis, measured within the plane of the ellipse. (b) Cross-section of the pelvis showing anatomical landmarks. Values of α greater than 30° should result in significant loading of the ilium, and values of $\alpha < -30^\circ$ should load the ischium. (c) Histogram showing the observed distribution of α.

3. Results

The large majority of trials caused sideways falls that produced direct impact to the lateral aspect of the hip (Table 1). Only 5% of participants were able to avoid falling altogether, and another 5% fell but did not impact the pelvis. The remaining 90% of participants fell and impacted the pelvis, and 98% of those cases involved direct impact to the hip region. The average hip proximity angle was 8° (SD = 15) to the posterior side (range = 63° posterior to 18° anterior; Fig. 2c). Pelvis impact velocity averaged 3.01 m/s (SD = 0.83), or 75% (SD = 20) of that predicted from simple free-fall dynamics.

Impact to the hands and knees was common (Table 1). Impact occurred to the left hand in 98% of falls, and in 95% of these cases, before pelvis impact. Impact occurred

Table 1
Frequency of impact to various body parts in trials that resulted in falls

Body part	Frequency ($n = 42$) (%)
Head	0
Left hip	93
Left hand	98
Right hand	64
Left elbow	60
Right elbow	0
Left knee	60
Right knee	2
Buttocks	2

Table 2
Frequency of various impact sequences during sideways falls that resulted in hip impact

Impact sequence	Frequency ($n = 39$) (%)
Left knee; left hand; left hip	31
Left hand; left hip; right hand	31
Left knee; left hand; left hip; right hand	23
Left hand; left hip	10
Left knee; left hip; left hand	5
Left hip; left hand	0

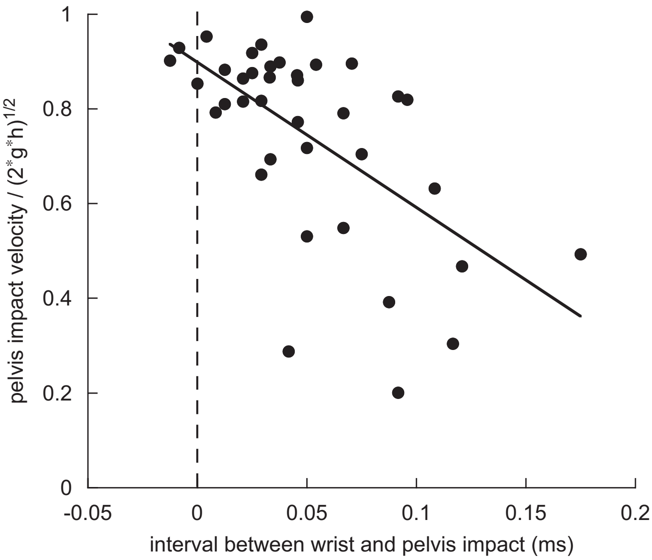

Fig. 3. Interval between hand and pelvis impact versus pelvis impact velocity. Pelvis impact velocity was normalized by the estimated free-fall impact velocity ($v = \sqrt{2gh}$, where $g = 9.81\,\mathrm{m/s^2}$ and h = height of the hip marker). The average interval between hand impact and pelvis impact was 50 ms (SD = 40), and the longer the interval the lower the pelvis impact velocity ($r = -0.6$; $p < 0.001$). On average, participants who were able to complete a step before their fall ($n = 9$) had a longer interval between hand impact and pelvis impact ($p = 0.001$), and a lower pelvis impact velocity ($p = 0.02$). Two trials involving no step were not included due to hand marker drop-out.

to the right hand in 64% of falls (19% before pelvis impact), to the left elbow in 60% of falls (25% before pelvis impact), and to the left knee in 60% of falls (100% before pelvis impact). Impact to the head was avoided in all cases, primarily by laterally flexing the trunk and impacting the outstretched hand(s). The average inclination of the trunk with respect to the vertical at the instant of pelvis impact was 42° (SD = 15).

The average time interval between the onset of the perturbation and impact to the pelvis was 626 ms (SD = 40). The most common impact sequence in trials that involved hip impact were (a) initial impact to the left knee, followed by impact to the left hand, and finally left hip, and (b) initial impact to the left hand, then the left hip, and the right hand (Table 2). The average interval between hand impact and pelvis impact was 50 ms (SD = 40; range = −12–175 ms), and only two participants impacted the hip before the hand. The impact velocity of the pelvis decreased 3.6% for every 10 ms increase in the interval between hand and pelvis impact ($r = -0.6$; $p < 0.001$; Fig. 3).

Sixty-two percent of participants exhibited an obvious attempt to recover balance by stepping (Fig. 4). Thirty-two percent of participants initiated but did not complete a step (Fig. 4a). Thirty percent of participants executed one or more complete steps, and in all of these trials the right (perturbation-unloaded) foot was lifted before the left. In 11% of trials, the right foot was swung medial and crossed anterior or forward to the left foot (Fig. 4b). In 14% of trials, the right foot was swung medial and crossed posterior or behind the left foot (Fig. 4c). In 5% of trials, the participant executed a two-step skipping or jumping movement, and these were the only participants to avoid falling (Fig. 4d). This skipping response involved the following chronology of events: (a) lifting of the right foot, (b) lifting of the left foot and a brief aerial phase where both feet were off the ground, (c) landing of the right foot in a location near to its initial position (medial to the left foot), and (d) landing of the left foot in a location lateral to its initial position. Participants who were able to complete a step before their fall ($n = 9$) took longer to impact the pelvis following the perturbation (691 ms (SD = 46) versus 613 ms (SD = 52), $p < 0.001$), had a longer interval between hand impact and pelvis impact (85 ms (SD = 47) versus 39 ms (SD = 31), $p = 0.001$), and had a lower pelvis impact velocity (2.46 m/s (SD = 0.94) versus 3.16 m/s (SD = 0.74), $p = 0.02$; Fig. 5).

4. Discussion

We found that sideways falls in young adults consistently result in impact to the hip region. This is considerably different than Hsiao and Robinovitch's (1998) finding that young individuals tend to avoid hip impact during sideways falls by rotating the trunk to face the impact surface, and landing on the hands and knees. We observed this technique only once. This discrepancy probably relates to differences in study design. Participants in Hsiao and Robinovitch's study were exposed to multiple perturbations of gradually increasing severity, and were provided

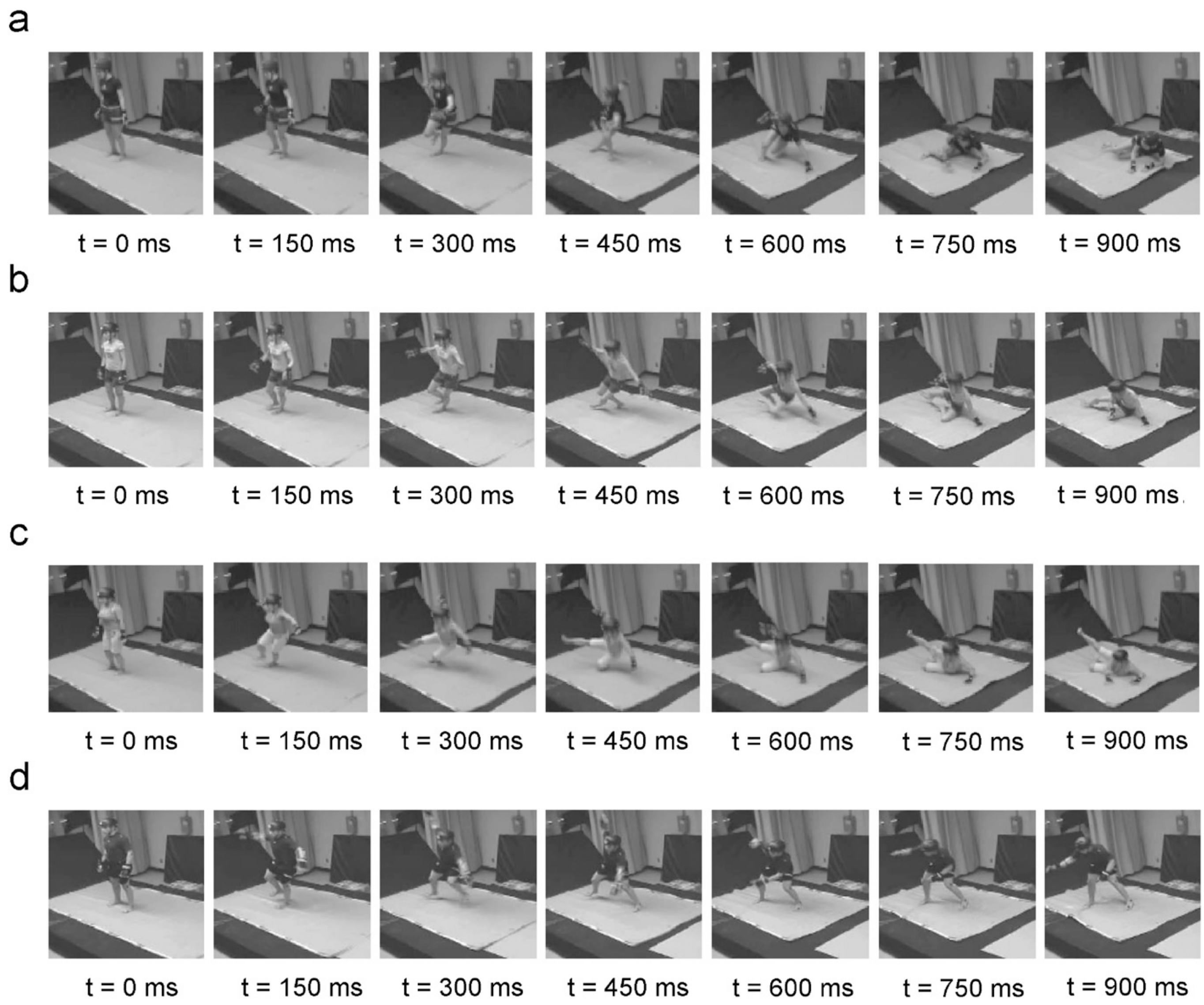

Fig. 4. Typical landing configurations during sideways falls. Individual panels illustrate (a) a cross-forward step followed by a fall, (b) a cross-behind step followed by a fall, (c) a partial step followed by a fall, and (d) a skipping movement resulting in balance recovery.

with a priori knowledge of the direction of the perturbation and the compliance of the ground surface. These factors probably assisted them in pre-planning their balance recovery and falling strategies. By eliminating the ability to practice and predict the nature of the perturbation, our current study design probably elicited falls that more closely resemble those occurring in real life.

We also found that the hand impacted before the hip in the vast majority of falls, and the knee impacted before the hip in most falls. Furthermore, the impact velocity of the pelvis decreased with increases in the time interval between hand and pelvis impact (which presumably influenced the energy absorbed by the upper extremity prior to pelvis impact).

Participants impacted their left hand in 98% of falls and in only two cases after hip impact. This differs from van den Kroonenberg et al.'s (1996) finding that impact to the hip precedes impact to the hand during sideways falls. van den Kroonenberg also reported a more upright trunk inclination at impact (21.7° (SD = 13.3)) with respect to the vertical, as opposed to our current value of 42° (SD = 15). These different outcomes again probably relate to differences in study design. In van den Kroonenberg et al.'s study, unlike ours, the sideways falls were self-initiated (and thus pre-planned) from standing, and the participants had knowledge of the low compliance of the impact surface.

Our results suggest that even unsuccessful attempts to recover balance by stepping may reduce risk for hip fracture during a fall. In particular, we found that taking a step (a) increases the time to pelvis impact, (b) increases the interval between hand impact and pelvis impact, and (c) decreases the impact velocity of the pelvis. Furthermore, the two participants who avoided a fall did so by using a

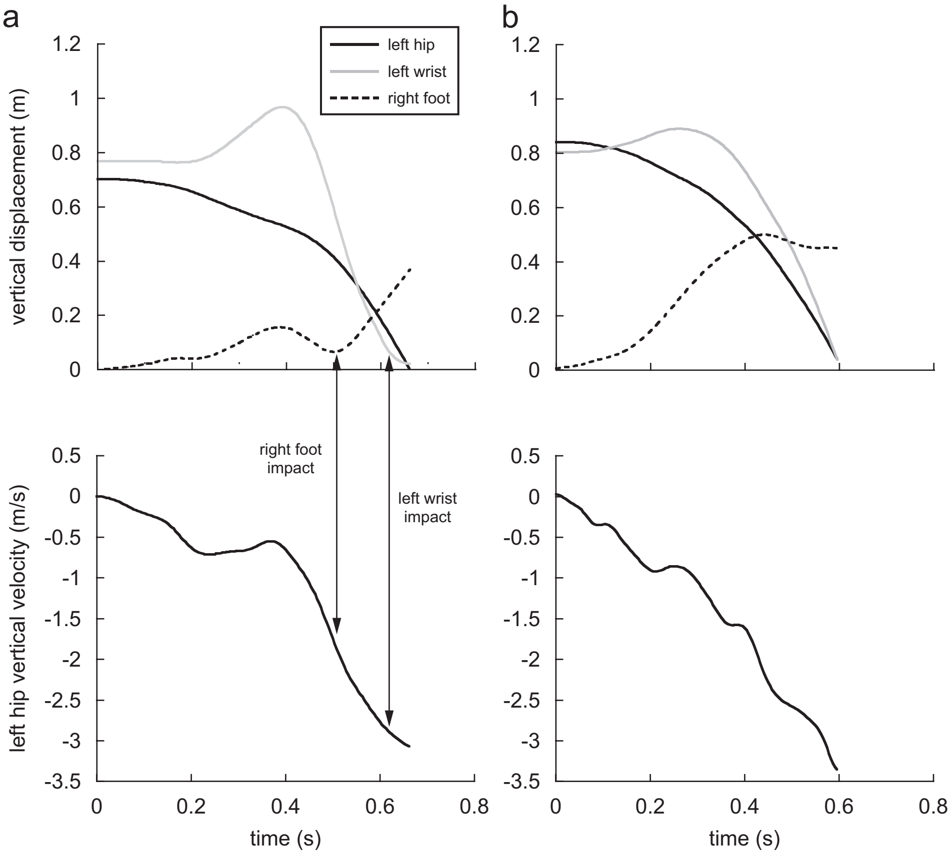

Fig. 5. Temporal variation in the vertical position of the left hip, left hand, and right foot markers (top) and vertical velocity of the left hip marker (bottom; negative velocity implies downward movement) for (a) trial involving a full step and (b) trial involving no step. The beginning of the traces ($t = 0$) represents the onset of perturbation and the end of the trace represents the instant of pelvis impact. In (a), the slope of the velocity trajectory is decreased by initial impact to the right foot and left hand.

two-step skipping or jumping movement that yielded a wide final stance. This sequence is similar to the "side-step" response to lateral platform translation described by Maki et al. (2000), which was especially common among elderly participants, and for perturbations applied while "walking in place." However, while we observed a distinct aerial phase in this step recovery pattern, they did not, perhaps due to the smaller perturbation strengths involved in their study.

It is difficult to elicit realistic falls in a laboratory environment, and our study had important limitations. First, although our participants were unable to predict the magnitude or direction of the perturbation, they did know that their balance would be perturbed in some manner. Thus, their preparedness (or "intentional set") was different from that which typically accompanies a real-life fall, and this may have altered their response. This is an inevitable limitation (given ethical considerations) on any laboratory experiments involving balance perturbations. Second, our participants performed a relatively basic motor task (quiet standing) before the onset of the perturbation, and additional studies are required to determine how fall mechanics are affected by the execution of more complex tasks, such as walking or turning (Smeesters et al., 2001), or holding an object (Bateni et al., 2004). Third, we examined only sideways perturbations to balance, and future studies are required to determine how falling patterns are influenced by the strength and direction of the perturbation (Hsiao and Robinovitch, 1998; Allum et al., 2002). Fourth, due to the compliant nature of the landing surface, we did not directly measure impact forces, but instead we estimated impact severity from impact sequence and impact velocity.

In summary, results from this laboratory study suggest that sideways falls in young adults commonly produce direct impact to the hip region, and that the severity of hip impact is reduced by initial impact to the hand and by stepping, both of which were common. These protective responses may help to explain why, in contrast to the elderly, fall-related hip fractures are relatively rare (but not unknown; Kannus et al., 2006) in young adults—even in sports such as soccer and basketball, where unpadded sideways falls are relatively common. An important goal for future studies is to determine how fall movements are affected by aging and specific neurological or musculoskeletal impairments. Are the common protective responses we observed preserved with aging, or replaced with alternative strategies? How do age-related declines in strength and reaction time influence the efficacy of these responses (Robinovitch et al., 2005; DeGoede et al, 2001)? A related but unexplored question concerns the practical benefit of exercise programs designed to "re-train" elderly men and women to fall in a way that is more protective to the hip. To address these questions, we will need to design experiments that are realistic enough to elicit natural falling responses, but safe enough for older adults to participate. This might be achieved through the use of hip protectors and additional protective gear, harnesses and elastic tethers to slow the rate of fall descent, or by having participants fall into a swimming pool or extremely soft mattress (although attention must also be directed to the possibility of injury, such as strains or sprains, during the balance recovery and descent phase of falling). Parallel efforts should seek improved evidence of movement strategies during real-life falls from video recordings in high-risk environments (Holliday et al., 1990) and wearable sensor systems (Bourke et al., 2006).

Acknowledgments

Supported by operating grants from the Canadian Institutes for Health Research (MOP- 64414) and Natural Sciences and Engineering Research Council of Canada (RGPIN/239735-2006). F. Feldman was supported by a fellowship trainee awards from the Michael Smith Foundation for Health Research. S. Robinovitch was supported by an MSFHR Scholar award and a Canada Research Chair. The authors wish to express their gratitude to Tony Leyland, M.Sc., who assisted greatly in participant recruitment.

Appendix A. Supplemental data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jbiomech.2007.01.019.

References

Allum, J.H., Carpenter, M.G., Honegger, F., Adkin, A.L., Bloem, B.R., 2002. Age-dependent variations in the directional sensitivity of balance corrections and compensatory arm movements in man. Journal of Physiology 542, 643–663.

Bateni, H., Zecevic, A., McIlroy, W.E., Maki, B.E., 2004. Resolving conflicts in task demands during balance recovery: does holding an object inhibit compensatory grasping? Experimental Brain Research 157, 49–58.

Bourke, A.K., O'Brien J.V., Lyons, G.M., 2006. (Epub ahead of print). Evaluation of a threshold-based tri-axial accelerometer fall detection algorithm. Gait Posture, in press.

Courtney, A.C., Wachtel, E.F., Myers, E.R., Hayes, W.C., 1995. Age-related reductions in the strength of the femur tested in a fall-loading configuration. Journal of Bone and Joint Surgery-American 77, 387–395.

DeGoede, K.M., Ashton-Miller, J.A., Liao, J.M., Alexander, N.B., 2001. How quickly can healthy adults move their hands to intercept an approaching object? Age and gender effects. Journals of Gerontology A: Biological Sciences and Medical Sciences 56, M584–M588.

Dietz, V., Noth, J., 1978. Pre-innervation and stretch responses of triceps bracchii in man falling with and without visual control. Brain Research 142, 576–579.

Greenspan, S.L., Myers, E.R., Maitland, L.A., Resnick, N.M., Hayes, W.C., 1994. Fall severity and bone mineral density as risk factors for hip fracture in ambulatory elderly. Journal of American Medical Association 271, 128–133.

Grisso, J.A., Kelsey, J.L., Strom, B.L., Chiu, G.Y., Maislin, G., O'Brien, L.A., Hoffman, S., Kaplan, F., 1991. Risk factors for falls as a cause of hip fracture in women. The Northeast Hip Fracture Study Group. New England Journal Medicine 324, 1326–1331.

Holliday, P.J., Fernie, G.R., Gryfe, C.I., Griggs, G.T., 1990. Video recording of spontaneous falls of the elderly. In: Gray, B.E. (Ed.), Slips, Stumbles and Falls: Pedestrian Footwear and Surfaces. American Society for Testing and Materials, Philadelphia, pp. 7–16.

Hsiao, E.T., Robinovitch, S.N., 1998. Common protective movements govern unexpected falls from standing height. Journal of Biomechanics 31, 1–9.

Kannus, P., Leiponen, P., Parkkari, J., Palvanen, M., Jarvinen, M., 2006. A sideways fall and hip fracture. Bone 39, 383–384.

Kim, K.J., Ashton-Miller, J.A., 2003. Biomechanics of fall arrest using the upper extremity: age differences. Clinical Biomechanics (Bristol, Avon) 18, 311–318.

Maki, B.E., Edmondstone, M.A., McIlroy, W.E., 2000. Age-related differences in laterally directed compensatory stepping behavior. Journals of Gerontology A: Biological Sciences and Medical Sciences 55, M270–M277.

Nevitt, M.C., Cummings, S.R., 1993. Type of fall and risk of hip and wrist fractures: the study of osteoporotic fractures. The Study of Osteoporotic Fractures Research Group. Journal of the American Geriatrics Society 41, 1226–1234.

Owen, R.A., Melton III, L.J., Johnson, K.A., Ilstrup, D.M., Riggs, B.L., 1982. Incidence of Colles' fracture in a North American community. American Journal of Public Health 72, 605–607.

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

Robinovitch, S.N., Normandin, S.C., Stotz, P., Maurer, J.D., 2005. Time requirement for young and elderly women to move into a position for breaking a fall with outstretched hands. Journals of Gerontology A: Biological Sciences and Medical Sciences 60, 1553–1557.

Sabick, M.B., Hay, J.G., Goel, V.K., Banks, S.A., 1999. Active responses decrease impact forces at the hip and shoulder in falls to the side. Journal of Biomechanics 32, 993–998.

Schwartz, A.V., Kelsey, J.L., Sidney, S., Grisso, J.A., 1998. Characteristics of falls and risk of hip fracture in elderly men. Osteoporosis International 8, 240–246.

Smeesters, C., Hayes, W.C., McMahon, T.A., 2001. Disturbance type and gait speed affect fall direction and impact location. Journal of Biomechanics 34, 309–317.

van den Kroonenberg, A.J., Hayes, W.C., McMahon, T.A., 1996. Hip impact velocities and body configurations for voluntary falls from standing height. Journal of Biomechanics 29, 807–811.