AUTOMATIC RECOGNITION OF FALLS IN GAIT-SLIP: A HARNESS LOAD CELL BASED CRITERION

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Abstract

Over-head-harness systems, equipped with load cell sensors, are essential to the participants' safety and to the outcome assessment in perturbation training. The purpose of this study was to first develop an automatic outcome recognition criterion among young adults for gait-slip training and then verify such criterion among older adults. Each of 39 young and 71 older subjects, all protected by safety harness, experienced 8 unannounced, repeated slips, while walking on a 7-m walkway. Each trial was monitored with a motion capture system, bilateral ground reaction force (GRF), harness force and video recording. The fall trials were first unambiguously indentified with careful visual inspection of all video records. The recoveries *without* balance loss (in which subjects' trailing foot landed anteriorly to the slipping foot) were also first fully recognized from motion and GRF analyses. These analyses then set the gold standard for the outcome recognition with load cell measurements. Logistic regression analyses based on young subjects' data revealed that peak load cell force was the best predictor of falls (with 100% accuracy) at the threshold of 30% body weight. On the other hand, the peak moving average force of load cell across 1-s period, was the best predictor (with 100% accuracy) separating recoveries *with* backward balance loss (in which the recovery step landed posterior to slipping foot) from harness assistance at the threshold of 4.5% body weight. These threshold values were fully verified using the data from older adults (100% accuracy in recognizing falls). Because of the increasing popularity in the perturbation training coupling with the protective over-head-harness system, this new criterion could have far reaching implications in automatic outcome recognition during the movement therapy.

Keywords

INTRODUCTION

An estimated 25% to 35% of adults aged 65 years and older fall each year (Tinetti, 2003). Slip-initiated falls account for about one quarter of all falls (Holbrook, 1984) and frequently cause hip fracture (Kannus et al., 1999). A better understanding of the mechanisms

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underlying slip-related falls will undoubtedly be a crucial step towards the prevention of such injuries. Real slip and fall reproduction in a lab environment is important to investigate the mechanisms behind slip-related falls (Lockhart, 2008; Pai and Bhatt, 2007; Redfern et al., 2001) as well to produce perturbation training for fall prevention (Pai and Bhatt, 2007; Pai et al., 2010). A widely-used method to reproduce real falls or balance loss is the gait-slip experiments. During these tests, subjects walk on a contaminated surface (Cham and Redfern, 2002; Lockhart et al., 2003; Troy et al., 2008; You et al., 2001), on a motorized force plate (Ferber et al., 2002; Tang and Woollacott, 1998), on a movable platform (Bhatt et al., 2006; Troy and Grabiner, 2006), or on a stroller (Marigold and Patla, 2002). To ensure the participants' safety, a harness system is essential during these experiments or in perturbation training that employ repeated slips (Pai and Bhatt, 2007; Pai et al., 2010).

Accurate classification of the slip outcome (fall vs. recovery) is critical to the proper assessment of the effectiveness of fall prevention training. Besides fall and recovery, harness assistance should be unambiguously classified (Brady et al., 2000; Pavol et al., 1999; Yang et al., 2009). False identification of a trial as a fall could lead to over or underestimating of the effect sample size or the training effect itself. When the harness system is set properly, visual inspection of the video recording can be used as a gold standard to judge falls in responding to a slip (Beschorner and Cham, 2008; Lockhart et al., 2003; Troy et al., 2008; Yang et al., 2009). A trial is usually categorized as a fall, if the subject's overall body posture is clearly and unambiguously in a falling mode that is only terminated when all the slack in the safety harness is taken away. However, this identification approach is time consuming, and is dependent upon the availability of the video recording. While the falling body posture and an actual fall can be unambiguously recognizable with visual inspection of video replay, such human cogitation and intelligence cannot be easily emulated at the present time for automatic identification with mathematical algorithm nor computer programming.

Alternatively, the kinematics of the slipping foot has often been considered as criterion variables to determine the slip outcome. However, the criteria of the fall based on slipping foot kinematics have been the subject of some disagreement among researchers. It was proposed that a slip was likely to result in a fall if the slip exceeded 0.1m in distance or 0.5m/s in velocity (Strandberg and Lanshammar, 1981). Another study indicated that falls were typically associated with slip distance exceeding 0.1m and peak slip velocity greater than 0.8m/s (Cham and Redfern, 2002). The thresholds of the slipping velocity causing fall were also reported at 1.44m/s and 1.07m/s for young and older adults, respectively (Lockhart et al., 2003). It was suggested that displacement rather than the velocity of the slipping foot would predict the outcome of slip (Brady et al., 2000). Given such wide discrepancies between the fall criteria employed by different researchers, a fall trial in one study could be a recovery in another.

Conceivably, because of the broad usage of the harness, the load cell force transmitted to the harness can provide means for automatic identification of recovery outcome. Previous studies used the harness load cell force (Brady et al., 2000; You et al., 2001) or its moving average over a period of time (Pavol et al., 1999) to classify slip outcome. Unfortunately, the thresholds of the load cell force to identify the slip outcome employed by different studies also varied drastically. For instance, Brady *et al.* proposed that the threshold load cell values to identify a fall is 50% body weight (*bw*) and the value for identifying a recovery is 8% *bw* (Brady et al., 2000). However, You *et al.* suggested that the threshold load cell value for a fall is 18.5% *bw* (You et al., 2001). None of these studies have explained the standard used to set these thresholds or have made systematic comparison with possible alternatives.

The purpose of this study was to first develop an automatic outcome recognition criterion among young adults for gait-slip training and then verify such criterion among older adults. The fall trials were first unambiguously indentified with careful visual inspection of all video records. The recoveries without balance loss, when subjects' trailing foot landed anterior to the slipping foot, were also first fully recognized from motion and ground reaction force (GRF) analyses. These slip outcomes classified based on such gold standard could then be used to determine the best thresholds for classifying slip outcome by systematically evaluating the load cell force and the moving average force over a range of 6 possible fixed intervals of 0.2s, 0.4s, 0.6s, 0.8s, 1.0s, or 1.2s.

METHODS

Thirty-nine young and 71 older subjects (Bhatt and Pai, 2009; Bhatt et al., 2006) gave written informed consent and were paid to participate in this institutionally approved study. Exclusionary criteria included a history of neurological or orthopedic disease. For young subjects, the mean ± SD age, body mass, and body height were 27.0±5.5 years (range: 19-38), 63.52±12.55kg, and 1.67±0.08m, respectively. For older subjects, the mean ± SD age, body mass, and body height were respectively 71.8±5.2 years (range: 65-90), 77.16±13.14kg, and 1.68±0.10m.

Subjects were informed that they would initially perform normal walking and later would experience a simulated slip, but they were unaware of the timing, location, or mechanisms involved before the first slip. They were also told to try to recover their balance on any slip and then to continue walking. An average of 10 regular walking trials preceded the first, novel slip. Also included in the present study were the next 7 consecutive unannounced slip trials in the first slipping block. In total, 312 and 568 slip trials were collected respectively from young and older subjects. An 8-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA) was used to determine the recovery (trailing) heel position at its touchdown relative to the slipping heel, and whether a backward balance loss had occurred.

Unannounced slips were induced as subjects walked along a 7-m walkway in which a sliding device was embedded. The sliding device consisted of a side-by-side pair of low-friction, passively movable platforms each mounted on a supporting metal frame with four linear bearings (Yang and Pai, 2007). The platforms were free to independently slide 0.75 m forward upon a computer controlled release of their locking mechanisms. Each metal frame was supported by two individual force plates (AMTI, Newton, MA) via two hinges in order to measure GRF to determine initial foot contact of a step. On the slipping trials, the right platform was released when the right foot contacted the movable platform; then the left platform was trigged when left foot touched it to perturb the recovery (left) step.

A full-body harness, attached by shock-absorbing ropes at the shoulders and waist to a low-friction linear bearing moving along a ceiling-mounted track, was employed for subjects' protection while imposing negligible resistance or constraint to their movement. The ropes were adjusted for each subject so that should they fall and suspend from the track after slip occurrence, their palms, knees, and buttocks would not contact the walking surface. After adjustments of the rope lengths, every subject was asked to perform a standard sitting-in-harness trial for 8 seconds to ensure their safety (Fig. 1-a). The full body kinematic data of that trial were actually collected from 24 out of 71 old subjects. The lowest-permissible hip height after the adjustment was $35.09 \pm 2.71 bh$ (body height) (Fig. 1-b), which approximates the lowest height that a subject's hip could reach under the constraint of the harness once a fall occurs.

A load cell connecting the rope to the bearing was used to measure the force exerted on the person. Its signal was sampled at 600Hz and low-pass filtered at 8Hz using a fourth-order, zero-lag, Butterworth filter during post-trial processing (Brady et al., 2000). The original force or the average force of the load cell over a pre-determined *moving interval* Δt, which was systematically tested at 6 different levels of 0.2s, 0.4s, 0.6s, 0.8s, 1.0s, or 1.2s, was computed across the 8-s data collection duration of each trial (Fig. 2). The moving average force, $y(t)$, of the load cell force, $LC(t)$, over Δt from the very beginning ($\Delta t/2$) to the end (8s- $\Delta t/2$) of data collection was calculated:

$$y_{\Delta t}(t) = \frac{\int_{t-\Delta t/2}^{t+\Delta t/2} LC(t)\, dt}{\Delta t} / bw \times 100\% \tag{1}$$

where, $y_{\Delta}(t)$ is the moving average force of the load cell over Δt.

Fall, recovery (with or without balance loss), and harness assistance are the three possible outcomes of each slip trial. First, each trial was carefully and visually inspected to determine if a fall had occurred (Fig. 3-a & b). If there was any ambiguity, the questionable trial would have been further reviewed by additional researchers for an independent decision. If a consensus could not be reached, that trial would have been excluded from further analysis. This situation had never occurred. Next, recovery without balance loss was also unambiguously identified from motion analyses when the subjects fully recovered from a slip with the recovery foot positioned anteriorly to the slipping foot (Bhatt et al., 2006). These analyses set the gold standard for the rest of the classification that differentiates falls, harness assistance, and recoveries because of their high certainty. The load cell force measurement of the trials in which the subjects had successfully recovered from slip-induced backward balance loss without harness assistance by landing their protective step posterior to the slipping foot after slip onset was expected to be comparable to those who recovered without balance loss (Fig. 3-c). Therefore, these trials were identified when the peak load cell force remained within the range of the mean (M_{LC}) + 3 standard deviations (3 SD_{LC}) of his/her own trials of recovery without balance loss (i.e., within 99.9% of the sample variability). Finally, when a fall did not occur the remaining trials would be classified as harness assistance, because of the high uncertainty associated with these balance loss recoveries that could have been achieved without harness support.

The threshold values of the force or moving average force of the load cell for this classification system were firstly derived based on the data from young subjects, and then were verified by the data from older adults. After each trial's classification was determined based on the aforementioned gold standard, the logistic regression analysis was employed to determine the threshold values of the peak force or peak moving average force of the load cell for slip outcome classification. These derived threshold values were then tested with the data from older adults by comparing the slip outcomes determined by these threshold values with the ones pre-determined by the gold standard.

There were two steps in the logistic regression analysis. Both steps involved examining the prediction accuracy for each of 7 predictors (including the load cell force, the moving average force of load cell over 6 different Δt) in predicting fall/non-fall (step 1) and recovery/harness assistance (step 2) and correspondingly computing the threshold value for each predictor. First, all fall (represented by 1 in the logistical regression analysis) and all non-fall trials (represented by 0, including recoveries and harness assistances trials) were input to the logistic regression analysis as the dependent variable and force or moving average force of load cell were the independent variables, i.e. the predictors. The regression equation, in the form of $p(\text{outcome}=1) = \frac{1}{1+e^{(b+kx)}}$, can thus be derived. Based on the

regression equation coefficients, the threshold value to differentiate fall and non-fall can be computed as $x = -b/k$ by assigning $p=0.5$ in above regression equation. Then, the recoveries (represented by 1) and harness assistances trials (represented by 0) were input to the logistic regression analysis as the dependent variable to determine the regression coefficients and thus the threshold value for classifying recovery and harness assistance. The threshold values based on the highest prediction accuracy across these 7 predictors would be applied to establish the slip outcome classification system. A cutoff probability for the threshold values was 0.5. A significant level of 0.05 was used throughout. Analyses were performed using SPSS 17.0 (Chicago, IL).

RESULTS

Based on the video inspections and $M_{LC} + 3SD_{LC}$ standard, 61(23 from young and 38 from older) trials were falls; 152 (68 from young and 84 from older) recoveries with balance loss, 654 (216 from young and 438 from older) recoveries without balance loss, and 13 (5 from young and 8 from older) harness assistances. The load cell force and the moving average force over 0.2s, 0.4s, and 0.6s could all discriminate falls from non-falls with 100% accuracy (Table 1). Other moving average forces have lower prediction accuracy of falls (Table 1). The load cell force would make the best distinction of 100.8% bw between fall and non-fall groups (Table 1). The threshold value of the load cell force is about 30% bw (Table 1, Fig. 4-a). The probability of falls by using the load cell force can be calculated by the following expression:

$$p\,(\text{fall}) = \frac{1}{1+e^{(19.81-0.66LC)}} \quad (p<0.05 \quad \text{for both coefficients}) \tag{2}$$

The moving average force of the load cell over 1s is the only predictor that can accurately differentiate recoveries from harness assistances. The threshold value of the moving average force is about 4.5% bw (Table 1, Fig. 4-b). The probability of recoveries based on the moving average force over 1 s can be obtained as,

$$p\,(\text{recovery}) = \frac{1}{1+e^{(-29.3+6.5y_{1-\text{sec}})}} \quad (p<0.05 \quad \text{for both coefficients}) \tag{3}$$

Verification of the slip outcome among 79 older adults by comparing the pre-determined ones by the gold standard with the ones decided by the derived threshold values indicated that the threshold values could precisely classify the slip outcome with 100% accuracy among these subjects (Fig. 5).

DISCUSSION

The load cell force or its moving average force could be applied to accurately classify the outcomes of gait-slip. The results of the systematic analyses revealed that falls can be differentiated from non-falls when the peak load cell force is greater than 30% bw (Fig. 4-a, region II in Fig. 5-b). Recoveries can be discriminated from harness assistances when the peak moving average force of the load cell over 1-s period is less than 4.5% bw (Fig. 4-b, region I in Fig. 5-b). When a trial's peak load cell force is less than 30% bw, and the peak moving average force over 1s is greater than 4.5% bw, it is a "harness assistance" (region III in Fig. 5-b).

The accurate identification of a fall is vital to the effects of reproducing true falls in perturbation training conducted in a protective environment, where "fall" is arrested by a harness, and where recovery from a slip is impossible without the use of a harness. The differences in criteria used to define a fall among studies clearly illustrated its difficulty

(Brady et al., 2000; Cham and Redfern, 2002; Lockhart et al., 2003; Strandberg and Lanshammar, 1981; You et al., 2001). The present study provides a rational approach using load cell in serial with the safety harness to classify outcome in response to a gait-slip perturbation. To the best of our knowledge, this represents the first attempt to systematically compare different possible load cell forces or moving average forces quantifications among such a large sample size to determine these threshold values. The proposed 30% *bw* for fall is generally comparable to but likely more precise than the wide range of the average maximum allowable forces used by other studies (Brady et al., 2000; You et al., 2001).

One strength of the study stems from the fact that the results derived from a smaller and younger sample are verifiable in a larger and (more appropriately) older sample (Fig. 5). The fact is that the threshold values from a smaller sample (*n*=39 with 26% of falls) can similarly predict the outcomes of a larger sample size (*n*=71 with 42% of falls). Because the falls occur in older adults more frequently, it is likely the findings will benefit older more than young adults. Given such stringent tests, the threshold values established here could indeed have high predictive power in classifying gait-slip outcomes. By logical extension, the threshold values are generally applicable to any falls irrespective of whether the individuals have movement disorders.

Although the threshold values to recognize slip outcome derived in this study was based on the perturbation induced by a movable platform, it could be generally used by other types of perturbation, such as containment surface (Cham and Redfern, 2002; Lockhart et al., 2003; Troy et al., 2008; You et al., 2001), motorized force plates (Ferber et al., 2002; Tang and Woollacott, 1998), and stroller (Marigold and Patla, 2002) as long as the adjustment of the ropes attached to the harness is similar across different researches (see below). One may argue that the gold standard of full recovery based on quantitative analysis of load cell force, i.e. using the $M_{LC} + 3SD_{LC}$ standard (Fig. 3-c) can be directly applied in practice, instead of using the load cell criterion of 4.5% *bw*. Actually, the M_{LC} and SD_{LC} in the present study were calculated across multiple repeated slipping trials where the subjects did not lose their balance. If a subject is only tested for a single trial or multi slip trials all resulted in backward balance loss, the $M_{LC} + 3SD_{LC}$ standard approach will be impossible to apply.

From the perspective of automatic recognition of recovery outcome, the load cell approach is ideal for processing "online" data that can be readily available with minimal delay and require minimal post-trial processing. Although human visual recognition is more sophisticated and accurate (Fig. 3-a) than any of the existing mathematical algorithm, visually inspecting video record replay can be very time consuming. In contrast, the load cell criteria to automatically judge slip outcome can now be easily integrated into perturbation training or assessment where the immediate outcome-based feedback is needed for the treatment. In addition, the load cell classification approach can also be implemented by computer programming for off-line outcome categorization. This will dramatically reduce the time-demand needed for determining the slip outcome.

While the lowest-permissible hip height after the harness adjustment was 35.09±2.71 *bh*, the actual lowest hip height in the present study measured during gait-slip was 34.89±2.90 *bh* and the two were not significantly different (*p*>0.05). These values provided us with means of direct quantification of the rope length setting. For fallers, the hip height at the instant when the load cell force reaches 30% *bw* is 39.97±3.44% *bh* (Fig. 1-b), which is significantly higher than the aforementioned lowest-permissible hip height (Fig. 1-b, *p* < 0.001). The load cell force generally reaches 30% *bw* before its peak value (Fig. 1-c) and therefore before most people's rope became fully stretched, which can only mean that the threshold values of the present study are not affected by the initial rope-length setting. Additional post-hoc analysis has been performed to estimate the impact if the rope-length setting were much

tighter than what has been applied in the present study. It was found that 100% of falls would still have been correctly classified if the initial lowest-permissible hip height were set at 39% bh. Still, 80% of falls would have been correctly classified at 40% bh, but only 53% correction at 42% bh. Such analysis implies that while a shorter rope-length setting might be desirable for frail or people vulnerable to fracture, a setting shorter than 39% bh might not be able to simultaneously and automatically provide accurate dual function of fall recognition.

The present study has limitations. First, the findings cannot be applied directly to monitoring and recognizing falls in real-life situations where a protective harness is unavailable. Second, as aforementioned, the accuracy of thresholds can indeed be dependent upon the rope-length setting of the harness system. Still, it should not be difficult to find a setting that can provide both safety to the subjects and automatic recognition of falls. Last, the threshold values were derived experimentally. A theoretical recovery limits below which an actual fall cannot be averted may be determined by model simulation (Pai and Patton, 1997; Yang et al., 2007), but this clearly is beyond the scope of this study.

In summary, this study developed the threshold values to differentiate falls from harness assistances or recoveries during gait-slip by using the force measured from the load cell or a transducer serially connected to the safety harness. Because of the increasing popularity in perturbation training and application of protective over-head harness system, this new criterion could have far reaching implications in automatic outcome recognition during the movement therapy.

Acknowledgments

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Research Highlights

1. Gold standard is established for identifying harness-assisted recoveries or falls.

2. The criteria for young adults are fully (100% accuracy) verified among older adults.

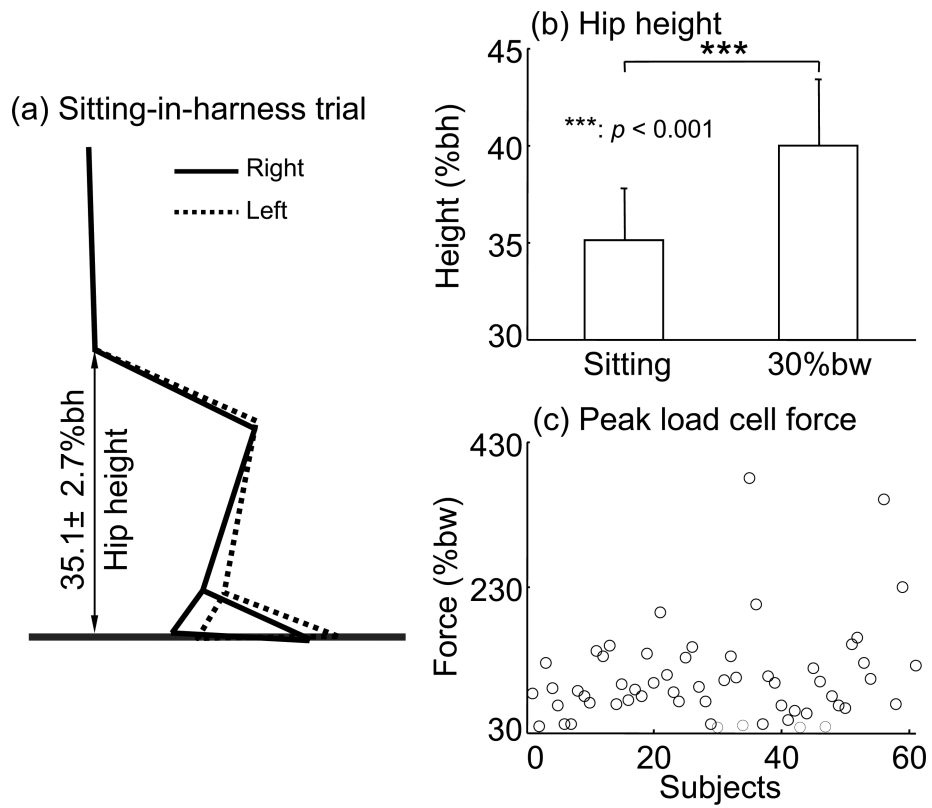**3.** The criteria provide immediate, automatic recognition of perturbation training outcome.

(a) Sitting-in-harness trial

35.1± 2.7%bh | Hip height

—— Right
········ Left

(b) Hip height

***: $p < 0.001$

Height (%bh)

Sitting   30%bw

(c) Peak load cell force

Force (%bw)

Subjects

Fig. 1.
(a) Schematic illustration showing the sitting-in-harness trial after the length of ropes connected to the harness was adjusted. Across 24 subjects whose full body kinematics was recorded during this trial, the mean ± standard deviation hip height was 35.09 ± 2.71% bh (body height). (b) Comparison of the lowest hip height allowed by the harness during the sitting-in-harness trial and the hip height at the instant when the load cell force reaches 30% body weight (bw) during gait-slip falls. (c) The distribution of the peak load cell force (represented as percentage of bw) for all fallers ($n = 61$) during slip induced in gait.
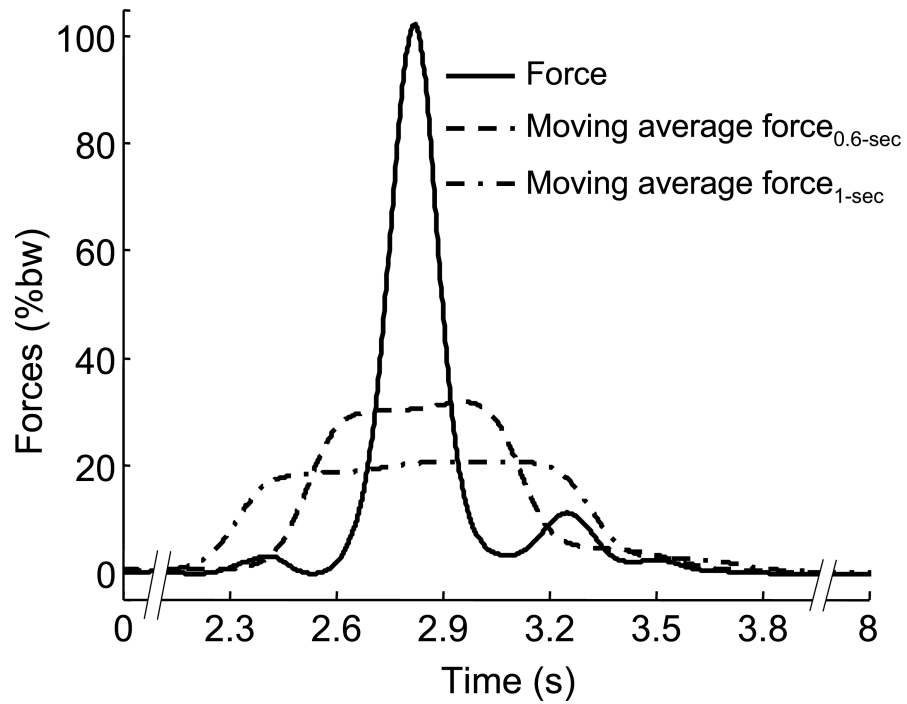
Fig. 2.
The load cell force profile for a subject (body mass = 61.3 kg, body height = 1.71 m) during a slip trial (the solid line). Also shown are the moving average forces of the load cell over 0.6 s (the dash-dotted line) and 1.0 s (the dashed line). All forces are normalized to the body weight (bw).
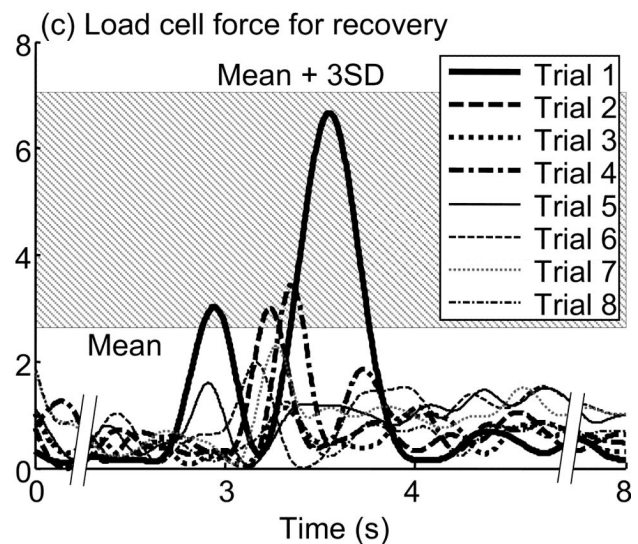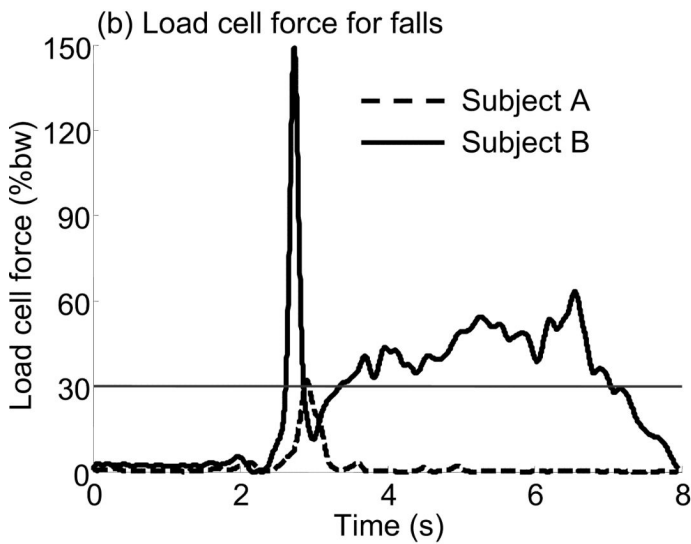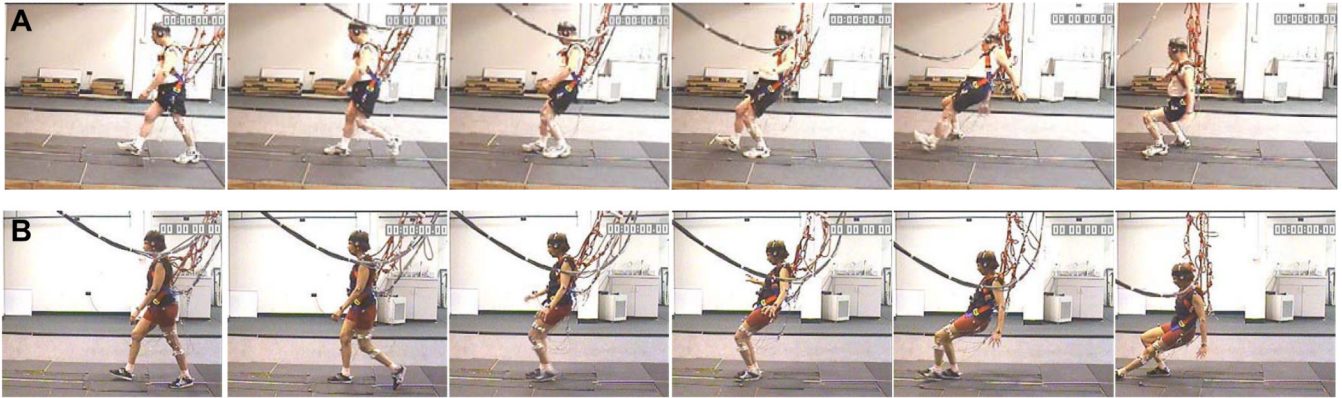
(a) Video for falls

Fig. 3.

(a) Video series and (b) time history of the harness load cell forces for two fall subjects during gait-slip trials. Subject A's peak load cell force was around 32% body weight (bw) which is close to the threshold value to determine falls as shown by a thin horizontal line in (b). It is apparent that a fall can be clearly identified by visual inspection even the peak load cell force near the threshold value. Subject B's load cell force is an exemplary one for fall; and (c) typical time history of load cell force for recovery during a gait-slip. In (c), also shown are the load cell forces recorded during 7 consecutive repeated gait-slip trials of a subject. The mean and standard deviation (SD) of the peak load cell forces (trials 2 through 7) are calculated. If the peak load cell force of the recovery with balance loss is less than mean + 3SD, the balance loss trial (trial 1) will still be a recovery rather than a fall. All forces are normalized to the bw.
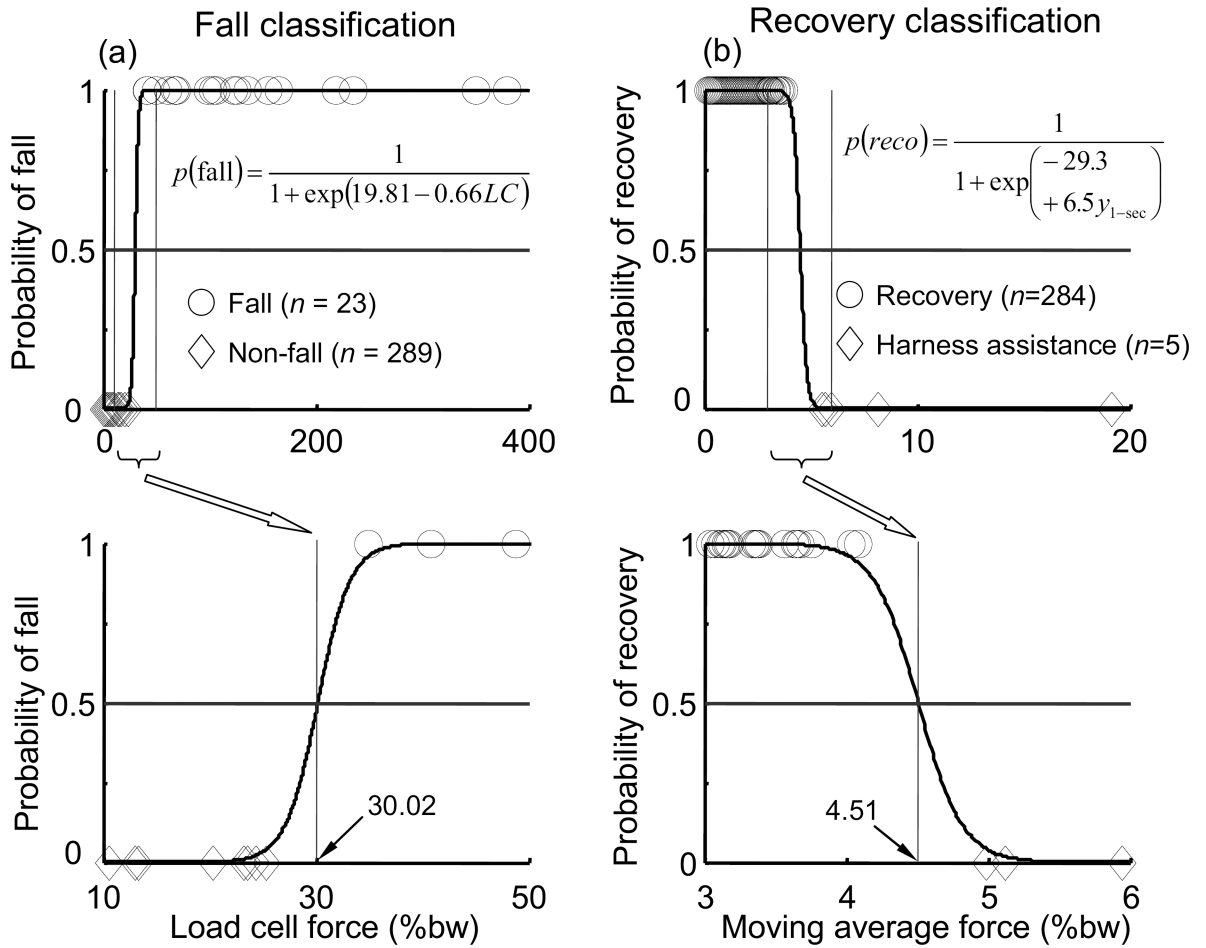
Fig. 4.
The logistic regression in which the probability of (a) fall and (b) recovery from a induced slip was predicted using (a) the load cell force and (b) the moving average force of the load cell over 1-s period, measured as percentage of the body weight (bw) correctly classified all of the slip outcomes. Data point for each trial is plotted as circle or diamond. A threshold probability of 0.5 (the thin horizontal line) was used for classification to determine the slip outcome. A portion of (a) and (b) between the two thin vertical lines were enlarged in the lower panel to illustrate more clearly the classification.
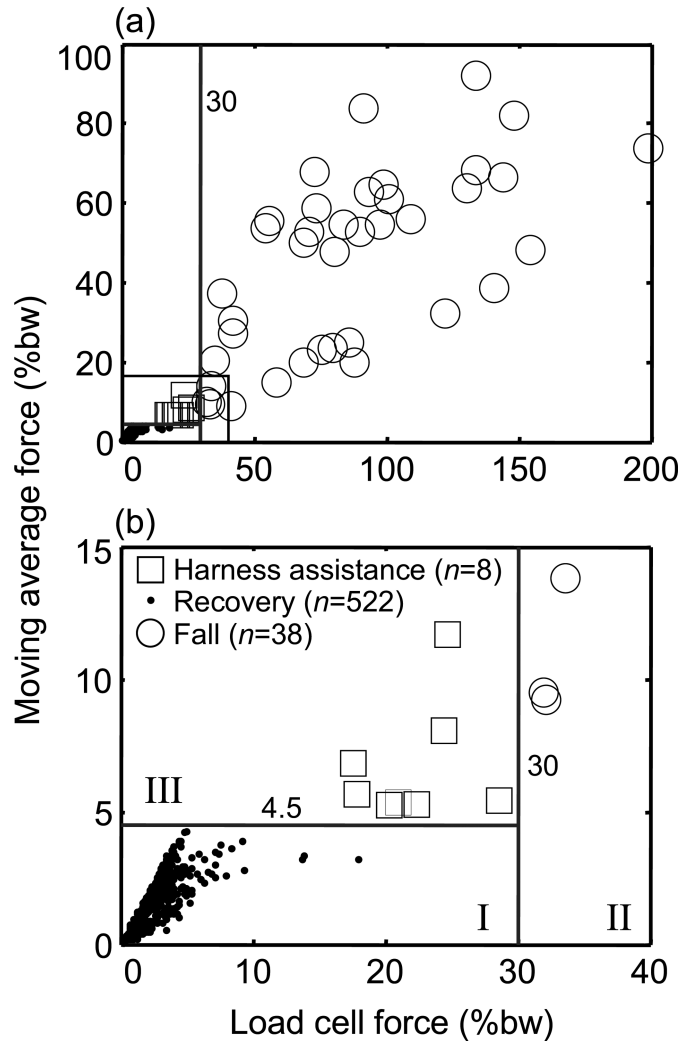
Fig. 5.
The distribution of the combinations of the peak load cell force and the corresponding moving average force over 1 s for all older subjects. Data point for each trial is plotted as circle (fall), dot (recovery), and square (harness assistance). Also shown are the threshold values to classify slip outcome derived based on the data from young subjects. The space formed by the moving average force and the load cell force is divided by these threshold values into three sections. Section I/II/III respectively corresponds to the recovery/fall/ harness assistance region. Both force and moving average force of the load cell are measured as percentage of the body weight (bw). A portion of the space in (a) is enlarged to illustrate more clearly the relationship between the distributions and the threshold values as (b).

Table 1

The prediction accuracy (%) of the slip outcome among young adults derived by logistical regression analysis using the load cell force, the moving average force of the load cell across various time interval, the maximum and mean ± SD values of load cell force and its moving average for fall and non-fall groups, and the threshold load cell value (in % body weight) for differentiating slip outcome. The best predictor is shaded for each category.

Predictor		Fall					Recovery				
		Fall (n = 23)	Non-fall (n = 289)	Max	Mean (SD)	Threshold	Recovery (n = 284)	Harness assistance (n = 5)	Max	Mean (SD)	Threshold
Force		100.0	100.0	380.1	103.9(67.9)	30.02	98.5	98.1	26.2	3.1(3.2)	14.79
Moving average force	0.2 s	100.0	100.0	360.4	84.9(58.8)	25.74	100	98.1	22.6	2.4(2.4)	10.28
	0.4 s	100.0	100.0	319.7	68.8(51.9)	18.52	98.5	98.1	21.4	2.0(1.8)	7.16
	0.6 s	100.0	100.0	306.8	62.9(50.5)	13.27	98.5	94.4	20.5	1.9(1.5)	5.68
	0.8 s	97.7	100.0	300.8	59.4(50.1)	11.24	98.5	94.4	18.9	1.8(1.4)	5.06
	1.0 s	97.7	100.0	293.1	56.9(49.5)	10.06	100.0	100.0	17.1	1.7(1.2)	4.51
	1.2 s	97.7	100.0	282.8	54.7(48.8)	8.87	98.5	94.4	14.8	1.7(1.2)	4.18