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LIMB COLLAPSE OR INSTABILITY? ASSESSMENT ON CAUSE OF FALLS

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Abstract

What causes an older adult to fall? Could the same factor lead to a recurring fall? The purposes of this study sought to address these questions by developing a causal-based assessment method for detection of the initial biomechanical cause of fall, and investigating the causation of 97 falls (out of 195 community-dwelling older adults who participated in this study) based on this method. The *unrecoverable* limb collapse, or *unrecoverable* instability, along with its point-of-no-return was defined, and the assessment method was established. Both the novel and the second slips of 97 participants who experienced laboratory-induced slip-related falls were assessed. The results showed that these older adults had more limb collapse (59.8%) initiated falls than instability (40.2%; and 32.0% of which from anteroposterior instability while only 8.2% from mediolateral instability) initiated falls. Interestingly, the majority (86.4%) of those 22 repeated fallers fell twice because of the same cause. These findings shed light on the vulnerability and the causation of recurring falls, which is one of the most challenging healthcare issues that an active but aging population is facing.

Keywords

Recurrent falls; point-of-no-return; causation; vulnerability

Introduction

Falls are serious and growing health concerns for older adults [15]. Slip-related falls account for about 25% of all falls among older adults [12]. The consequences of falls include hip/arm fractures, traumatic head injuries, and even death [17, 31]. Up to 12% of hip fractures result from slip-related falls [18]. Extensive efforts have been made on designing fall prevention and balance improvement programs, ranging from muscle-strengthening training, multisensory training, Tai-Chi practice, to slip perturbation training; each may yield different effects [14, 20, 25, 30, 35]. Individualized assessment on the biomechanical causation of falls, however, had hardly ever been performed [13]. Approximately 50% of older adults experience recurrent falls within one year after their first fall [7]. Unlike those accidental single falls, the recurrent

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falls are often associated with increased mortality [3]. Before we can effectively formulate prevention strategies to reduce such risks, it begs the question that how often would the recurrent falls be caused by the same biomechanical factor,.

Previous studies have identified two biomechanical causes for slip-induced falls in walking [26, 38]. One is related to one's limb support against gravity (in vertical direction) while the other relates to one's control of stability (in horizontal plane). After a balance disturbance, a person must keep the center of mass (COM) from crushing towards the ground. Deficient limb support would lead to *continuous* vertical descent, and such descent is considered as *unrecoverable* limb collapse [38]. The beginning of this perpetual descent can be identified as the *point-of-no-return* of limb collapse.

The COM instability occurs when its motion states, determined collectively by its *horizontal* instantaneous position and velocity relative to the base of support (BOS), exceed the stability limits [22]. The instability can take place in anteroposterior (AP) and/or in mediolateral (ML) directions [23, 36, 39]. Like unrecoverable limb collapse, *unrecoverable* instability occurs when a person can't recover from perturbation-induced instability which would lead to a fall. Similarly, the beginning of the unrecoverable instability prior to a fall is considered as the *point-of-no-return* of instability.

What causes an older adult to fall? Previous studies found poor limb support in vertical direction and AP instability together accounted for 88.9%−100% of all slip-related falls [37, 38]. Although these studies did consider causal factors, they did not consider ML instability, nor did they inspect individual cases and identify the sequence of events when one or more of these factors emerged. These multiple factors are not equal in terms of their contributions to the fall and each has a point-of-no-return. Chronologically, the earliest point-of-no-return, which has occurred upstream in the sequence of events, must have the dominant effect leading to this fall. Furthermore, while recurring falls have been identified as one of the most prominent risk factors for predicting future falls [28, 33], would a specific weakness cause a person to fall repeatedly?

The purposes of this study were to address these questions by developing a causal-based assessment method, and investigate the causation of 97 falls (out of 195 community-dwelling older adults participated in this study) based on this method [24, 34]. We first hypothesized that these participants were equally susceptible to the above-stated causal factors (null hypothesis). We further hypothesized that the repeated falls would likely result from the same cause. A dominant vulnerability could justify the inclusion of a specialized rather than overly generalized interventions or approaches in future, targeting individualized vulnerability.

Methods

1. The cause of falls

To provide adequate limb support and to maintain stability are two of the most essential requirements of balance control in daily activities such as walking. Moving through a three-dimensional space, falls could result only from failure in limb support (in vertical direction) or from failure in the control of stability (in horizontal motion of the COM relative to its BOS, *i.e.*, either in AP or in ML direction). This notion was supported by previous observations where all (100%) of falls could be accounted for by one of these failures [38].

Unrecoverable limb collapse—Limb support can simply be quantified by subtracting the body weight (BW) from the vertical GRF [or $(GRF - BW) \times BW^{-1}$, as normalized by BW]. While the amount of limb support can fluctuate cyclically in walking, the waning (descending) in the support of the COM vertical position is always followed by its expanding (ascending), except in an actual fall. The **necessary condition** for limb support failure concurs with *continuous* waning of this limb support [$(GRF - BW) \times BW^{-1} < 0$]], when the COM accelerates *monotonically* downward (Fig. 1). The **sufficient condition** for such failure would be met when the knee flexion angle of the supporting lower limb(s) increases *continuously* and *monotonically* resulting in a flexion decay. Both conditions must be met for the identification of limb support failure in *Unrecoverable* limb collapse (Fig. 2).

Unrecoverable instability—In a regular walking cycle, stability also fluctuates in a cyclical manner. While spontaneous AP and ML instability are useful for forward progression and mobility, such instability is always reversed while stability recovers upon the next step (Fig. 2). Stability can be measured at any instant by the closest distance from a person's relative motion state to the limits of stability, where this motion state is quantified by the relative instantaneous position and velocity in the horizontal plane (either in AP or in ML direction) [22, 36, 39]. Balance loss must occur when the instantaneous motion state is located outside of the limits of the stability ($S > 1$ for forward balance loss as in walking, or when stability $S < 0$ for backward balance loss as in a walk-slip, here S indicates the value of stability) (Fig. 2).

Following a slip, a person can experience severe destabilization posteriorly as the BOS of the leading foot inadvertently shifts in the anterior direction much faster than the forward moving COM. In these cases, the COM stability cannot be restored without taking a protective stepping, landing posteriorly to the slipping foot. Failure in the restoration of stability (*unrecoverable* instability) occurs when stability measure remains continuously outside limits of stability ($S < 0$) and **never** returns to inside of stability limits ($S > 0$) until an actual fall or being caught by harness fall-arrest, regardless whether it occurs in AP or in ML direction (Fig. 2).

Point-of-no-return—A fall can result from a single failure, whether it is from unrecoverable limb collapse (with its onset marked as T_{limb}), or from unrecoverable instability (either in AP or ML direction, with onset timing as T_{sta_AP} or T_{sta_ML}, respectively). In these cases, the determination of the cause would be simple, and the onset of that *single* failure would be considered as the *point-of-no-return*. When two or three (*duo or triple)* failures occur, the first failure (T_{sta_AP}, T_{sta_ML}, or T_{limb}) will be considered as the *cause* of the fall (Fig. 2). If more than one failure occur simultaneously, all these failures would be considered as the *causes, i.e.,* a fall from *multiple-factor* failure.

2. Assessment of falls

Participants—195 participants (≥ 65 years old) participated in this study, all of them were screened via questionnaire before their laboratory sessions to exclude neurologic, musculoskeletal, cardiopulmonary, and any other systemic disorders. This study has a supervisory structure that included a geriatrician on board, and was under the supervision of the Institutional Review Board (IRB). The research was carried out under the supervision of a NIH program officer, who must ensure that the research is in compliance with its standards and policies, including any concerns related to the participants enrolled in the study. All participants signed informed consent, which had been approved by the IRB at the University of Illinois at Chicago. 111 participants fell in their novel slip trials. Among them, 14 participants were either assisted by the experimenter or stepped out of the force plates before they fell. Those participants were excluded to avoid inconsistency. Among the remaining 97 fallers (age: 72.0 ± 4.9 years; height: 163.8 ± 7.3 cm; mass: 75.7 ± 14.4 kg) included in this study, 22 fell again in the subsequent slip trial.

Experimental setup—The slip was induced by releasing a pair of side-by-side, low-friction, movable platforms embedded in the middle of a 7-meter walkway. During the slip trial, a computer-controlled triggering mechanism would release the movable platforms to slide freely in the AP direction once a participant’s right (slipping) foot landed on it.

Participants began with 10 regular walking trials, and were only told that a slip “may or may not happen” on any of the trials. Unannounced slips were organized in 3 blocks of 8 trials, interposed by 2 blocks of 3 unannounced non-slip trials. Only the first two slips were included in the present study due to the drastic reduction in the number of participates who would fall again after these two trials [19]. In fact, while 97 participants fell on the first trial, only 22 fell again in the subsequent trial. Because the moveable platforms were surrounded by stationary decoy platforms, participants were unaware of how, where, or when the slip would occur.

The participant wore a full-body safety harness which provided protection against body impact with the floor surface while enabled participant to walk freely. The harness was connected to a loadcell (Transcell Technology Inc., Buffalo Grove, IL) via shock-absorbing ropes[6]. The loadcell was mounted on an overhead trolley on a track over the walkway. Kinematics of a modified Helen Hayes full-body marker set using 30 retro-reflective markers was recorded by an eight-camera motion-capture system (Motion Analysis Corporation, Santa Rosa, CA). Kinematic data were sampled at 120 Hz and synchronized with the force plate and loadcell data, which were collected at 600 Hz.

Limb support measurement—The vertical ground reaction force derived from 4 (2 on right side, and other 2 on left side) force-plates (AMTI, Newton, MA) was used to measure limb support [$(GRF - BW) \times BW^{-1}$]. Unlike stability measure that could employ analytically limits of stability, limb support measure does not have a threshold below which a failure could be detected. Instead, a pair of above stated empirically-derived “necessary” and “sufficient” conditions were employed to define the failure.

Stability measurement—The COM position and its velocity relative to those of the BOS were computed in AP and ML directions to assess a person's instantaneous dynamic stability [22, 36, 39]. First, these COM kinematics were calculated based on body segment coordinates using a 13-segment rigid body model[6]. The rear edge of the right heel and its velocity were used as BOS reference to calculate the relative COM state. Then, the relative COM position in AP or ML direction was normalized by the length or the width of BOS separately. The relative COM velocity was normalized by the quantity $\sqrt{g \times BH}$, where g is the gravitational acceleration and BH represents the body height. Finally, the normalized COM stability measure (S) was computed as the *shortest* distance from the COM state to the limits of stability under slip conditions and during walking in AP and ML directions [36, 39].

The feasible stability region lies between the upper ($S = 1$) and lower ($S = 0$) limits of stability. When the normalized stability value drops below 0, a balance loss must occur in posterior direction or in contralateral direction to the stance limb [22, 36]. Balance loss could be recovered by taking a step landing in the direction of the instability. A forward loss of balance occurs in regular walking when the stability value exceeds 1. A step in the forward direction can restore stability ($0 < S < 1$). Similarly, a backward loss of balance following slip onset can be restored by taking a step landing posterior to the slipping foot (changing from $S < 0$ to $S > 0$ in Fig. 2).

Timing of events—The event time in the slip gait was determined from force plate data which included slipping foot (right) touchdown (RTD), slip onset, recovery foot (left) liftoff (LLO) in protective stepping and its touchdown (LTD). Fall and recovery were two outcomes of a slip. A harness (fall) arrest occurred when the peak loadcell force exceeded 30% BW during a slip recovery [40], while its onset (T_{fall}) was identified when the loadcell value began to rise above 10% BW. The time-of-no-return for each failure was determined based on the corresponding variable's time history that satisfied the above stated criteria.

In order to understand the severity of the stability loss and weight support loss prior to the touchdown of the protective stepping, we compared the differences in these variables from LLO to the pre-LTD time (LTD - 10 ms). The 10 ms interval was chosen to ensure that this instant was before any contact that the force plate could have detected. To understand the amount of the gain from the touchdown of the protective stepping, we also compared the differences in in the same variables from pre-LTD to post-LTD (LTD + 80 ms). This 80 ms was chosen to represent the amount of time the landing (decelerating) foot took to deceleration to 0 after its touchdown [5].

Statistical analysis—Independent t-tests were performed to compare the age, body mass, body height and BMI between feet-forward and split slip groups. Chi-square test was used to examine the difference in gender between the two groups. To test the first hypothesis, Chi-square goodness of fit test was used to examine the probability of cause of falls for the 97 trials. To investigate the effectiveness of protective stepping in recovery, paired t-tests were used to compare the magnitude of the pre-LTD loss with that of the post-LTD gain in each variable. To test the second hypothesis, McNemar Chi-square test was used to determine whether the fall causes changed from the first falls to the second falls for 22 participants (44 trials). All statistical analysis was performed using SPSS 22 (IBM Corp, Armonk, NY). P-values below 0.05 were considered statistically significant.

Results

These older adults were more likely to fall from limb collapse ($X^2 = 39.95$; $p < 0.001$) than from failed stability recovery. Unrecoverable limb collapse caused 58 (59.8%) falls, and the remaining 39 (40.2%) falls came from unrecoverable instability (Fig. 3). Among them, 31 (79.5%) resulted from AP instability and 8 (20.5%) from ML instability (Fig. 3). Notably, 35 of 58 limb collapse (60.3%) and 17 of 40 instability (42.5%) resulted from a *single* failure (displayed on the top and the right margin of Fig. 3, respectively). 21 of 58 limb collapse (36.2%) and 15 of 40 instability (37.5%) had a *duo* failure (Fig. 3). Only 8 of 97 fell from a *triple* failure (7 had AP instability failure first, 1 had ML instability failure first). None had any *multiple-factor failure* (more than one factor occurred *simultaneously*) in these 97 initial falls or in 22 subsequent falls. There was no fall-cause-related difference in age and body height ($p > 0.05$ for both). Females ($p < 0.001$) or individuals with higher body weight ($p = 0.001$) and BMI ($p < 0.001$) tent to fall due to limb collapse (Table 1).

Slip weakened limb support while it induced severe instability (limb support loss: 0.08 ± 0.21; AP stability loss: 0.91 ± 0.30; ML stability loss: 0.01 ± 0.03, Fig. 4). Protective stepping could significantly improve both (limb support gain: 0.22 ± 0.25; AP stability gain: 0.61 ± 0.39; ML stability gain: 0.03 ± 0.04, $p < 0.001$ for all, Fig. 4). However, *before* the recovery foot touchdown, 28 individuals' eventual fall was already determined (26 from limb collapse and 2 from AP instability, Fig. 3).

The reason for most of those 22 repeated falls remained unchanged (limb collapse: 13/22 or 59.1%; AP instability: 6/22 or 27.3%, $X^2 = 1.33$; $p = 0.25$, Table 2 and Fig. 5). Only 3 participates (13.6%) fell from limb collapse in their first trials while fail from ML instability in the second trials (Fig. 5).

Discussion

This paper sought to address two fundamental questions in order to reduce the likelihood of falls among community-dwelling older adults: What causes most community-living older adults to fall upon a slip while walking? Would the same vulnerability cause them to fall again in a repeat slip? To find the answers, we developed a causal-based assessment method that relies on the concept of unrecoverable limb collapse, unrecoverable instability, and the point-of-no-return, together with the actual recording of their limb support and stability time history taken during the laboratory-induced slips.

The results did not support the first (null) hypothesis. More participants fell from unrecoverable limb collapse than unrecoverable instability (59.8% vs. 40.2%, Fig. 3) -- a finding that might lend support from the long-held notion of age-related deterioration in muscle strength [4, 16]. To mitigate the muscle weakness, the best protective step for improving weight support is to place the recovery foot *directly* underneath the COM, thus the ground reaction force (GRF) can be maximized to reverse COM vertical descent. Yet, there is a contradiction about the cost associated with such a response. The BOS does not extend sufficiently posterior to reverse the slip-induced instability. The needs for limb support contradict with the needs for stability recovery with respect to the landing location of the recovery foot. An extremely alternative strategy is to abort step and to keep the trailing foot as far posterior to the COM as possible to maximize stability [2]. In that case, both feet would remain on the ground while both feet can yield a large BOS for maintaining stability. Yet, an aborted stepping would require a complete halt of ongoing motor programming (from central pattern generator) for walking [27], which most participates (84/97 or 86.6%) either did not or could not do. Still, the results could be interpreted as that these individuals instinctively favored restoring stability over the needs for limb support upon the fleeting instants following the balance disturbance.

While this protective stepping can bring substantial post-touchdown gains (Fig. 4), both limb support and stability would have sharply deteriorated from its liftoff to touchdown (Fig. 4). This is another contradiction. Taking such a recovery step would require change from bipedal to single-stance. The change would momentarily but inevitably weaken not only a person's weight support, which would have fallen on just a single limb, but also his or her stability due to the abrupt reduction in the BOS (Fig. 4). This contradiction puts the post-touchdown gains against the single-stance phase losses. Though the latter was even greater than the former in AP stability control, such a protective step nonetheless restored a significant amount of instability (Fig. 5a). Still, such momentary losses during single stance phase were so severe; in fact, some participates (28/97 or 28.9%) reached the "point-of-no-return" (unrecoverable limb collapse or unrecoverable AP instability) before their recovery step touchdown (Fig. 3). Most of these falls (26/28 or 92.9%) resulted from limb collapse (Fig. 3). In these cases, the improvement in weight support came too little and/or too late after touchdown to compensate for the losses. For these participates, the aforementioned aborted step strategy might be a better option. It is noteworthy; however, 6 out of 8 falls from ML instability came from either aborted-step or near aborted-step strategy, suggesting a third tradeoff (contradiction) might exist between keeping AP versus ML stability.

The results *did* support the second hypothesis. A majority (19/22 or 86.4%) of those who fell in second slips had the same cause as in their first slip. The learning from the "first-trial effect" was extremely powerful, and most participates made sufficient adaptation and did not fall again [1]. Hence, such vulnerability appeared repeatedly should call for special attention. While generalized interventions for fall prevention have been widely used in practice [8, 10, 32], no individualized-treatment was established according to the specific weakness of a group of participants. Thus, the development of assessment tools to identify such vulnerability among older adults is imperative. Only when reliable assessment tools are available, such targeted treatment can then be formulated (Fig. 6). For example, because limb collapse might be related to the deterioration in muscle strength and improper recovery foot landing location, Tai-Chi [35] that requires a semi-squat posture during practice can be especially effective in addressing the vulnerability to limb collapse. Tai-Chi also places high emphasis on volitional control of foot placement, which could also improve protective stepping (Fig. 6). There is a range of perturbation training emerging that can address one's deficits in making reactive recovery stepping [9, 21]. While hip abductor-adductor motion control and trunk motion control are crucial for sustaining sideways postural balance [29], trunk muscle strength training might be helpful for fallers from ML instability [11]. With the help of the assessment method developed in the present study, pinpointing the vulnerability to falls and devising individualized treatment plan could be a part of the intervention to reduce the likelihood of falls among community-living older adults.

Notably, there are at least two analytical (as versus stochastic) approaches that can be applied to establish the causation of some end results, such as falls in the present study. One of them is to first establish an exhaust list of possible causes, and to establish a complete time history of if and when these events have taken place. By eliminating those that have not happened, the remaining cause that has first occurred should logically be considered as the primary culprit. The other approach does not have to consider all possible causes, and it does not have to worry about the entire history. Rather, this approach relies on the direct manipulation of a specific factor, such as strengthening or weakening one’s limb support to determine whether it is a causal factor. The outcome of the manipulation could either rule-in or rule-out such as causal factor.

While both approaches could be valid, the first approach does not need to introduce artificial disturbance – it judges as a matter of fact. Yet, the first approach carries the burden of identifying all possible causes, exhaustively. Any omission of possible culprit will weaken the strength of the analysis. In this particular case, the control of human upright mobility has *only* three ways to fail – two in the horizontal plane, and one in the sagittal plane. The second approach is better suited in model simulation, in which the investigator can take the liberty to both control all other potential factors while manipulating one single factor. Yet, by artificially controlling or inducing disturbance to possible causal factors, the end results no longer belong to what have just happened to that *particular individual* anymore.

Finally, there are different layers of causations for the failure of a movement. What we were able to identify here are merely the biomechanical causes of movement failure, which perhaps can be considered as the most “downstream” causal factors, the ones that can be visible and directly measureable. Joint moments, once considered as the direct product through the neurogenic “final common pathway” in the creation or the causation of human motion, can be another layer (“upstream” level) of causation.

Further “upstream” causation could involve different motor centers and the sensorimotor integration. Moreover, factors such as a person’s individual muscle morphology, anatomy, gender (Table 1), metabolic state, or even genetics and diet can all play a role in the stochastic analyses for the risk of falls. These factors can hardly be controlled or directly manipulated in reality. It is noteworthy that these different layers of (potential) causations are *not mutually exclusive*, and the complexity of these considerations is far beyond the scope of the present study.

In summary, this study developed a mechanistic-based method to assess the cause of falls for each individual laboratory-induced fall by the identification of unrecoverable limb collapse or unrecoverable instability in AP or ML direction during the slip gait. Unrecoverable limb collapse was a major cause of falls as well as the cause of repeated falls among the participants of the present study. Future studies may further demonstrate the efficacy of individualized-treatment for fall prevention among older adults.

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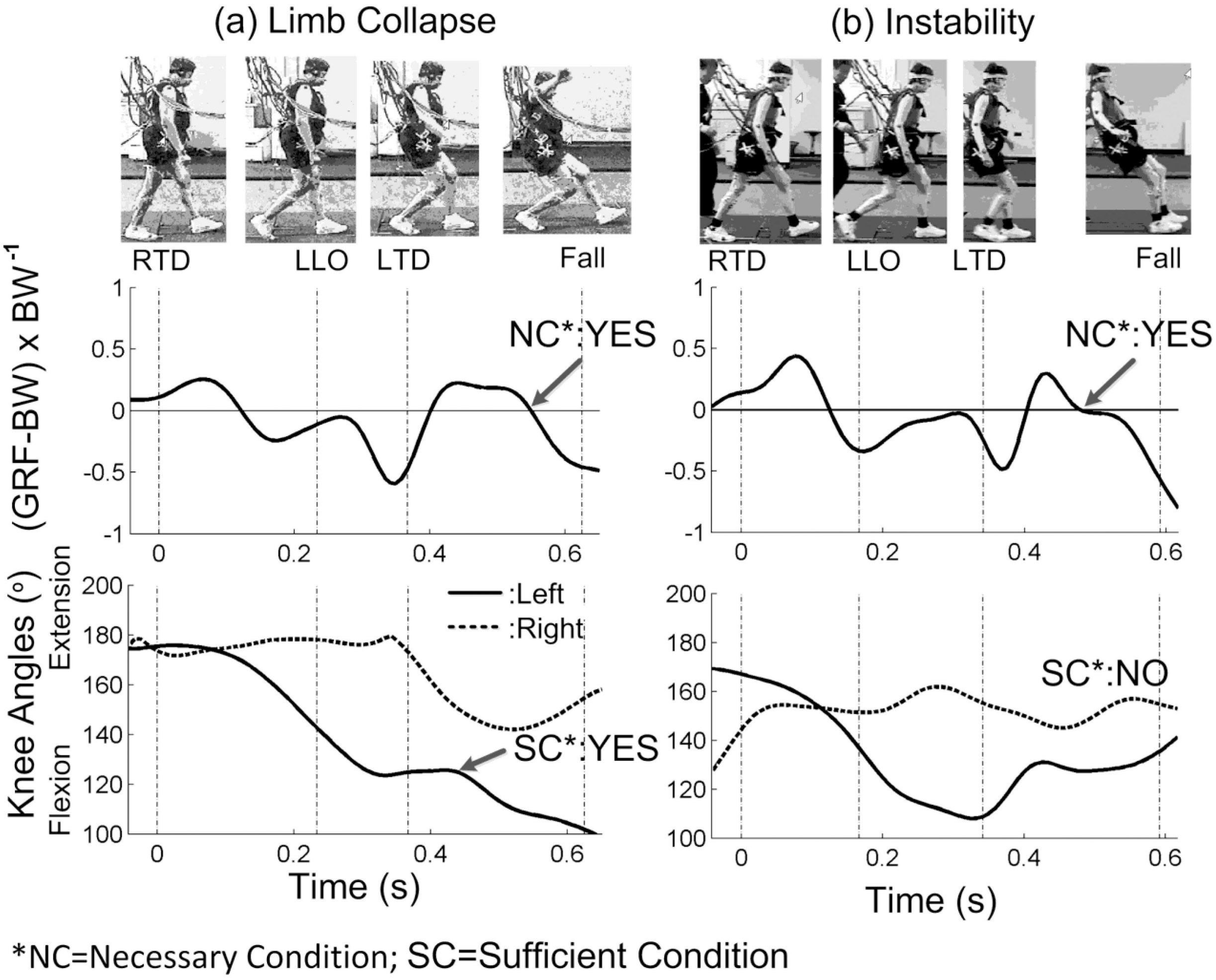

Figure 1.

(a) An example of fall from unrecoverable limb collapse. An arrow in the top panel makes the time when the necessary condition (NC) is satisfied (YES), as the ground reaction force (GRF) began to decay continuously and monotonically until harness fall-arrest and became insufficient to support the body weight (BW) [(GRF-BW) < 0]. The arrow in the bottom panel makes the beginning when sufficient condition (SC) for unrecoverable limb collapse is met (YES), as the left knee (thick solid line) flexed continuously and monotonically in a flexion decay. The point-of-no-return in limb support failure begins when both conditions are met. In the example, the sufficient condition was met first, and hence the onset of limb collapse was determined by the necessary condition. (b) In this case, while the necessary condition for limb support failure was satisfied (top panel, YES), the sufficient condition was never met (bottom panel, NO). This fall in fact resulted from anteroposterior (AP) instability (not shown here). The dotted vertical lines indicate the onset timing of leading (right) foot touchdown (RTD), recovery foot (left) liftoff (LLO), and its touchdown (LTD). Still-frame video images of sagittal view were shown at the instant of RTD, LLO, LTD, or at the onset of harness fall-arrest (Fall).

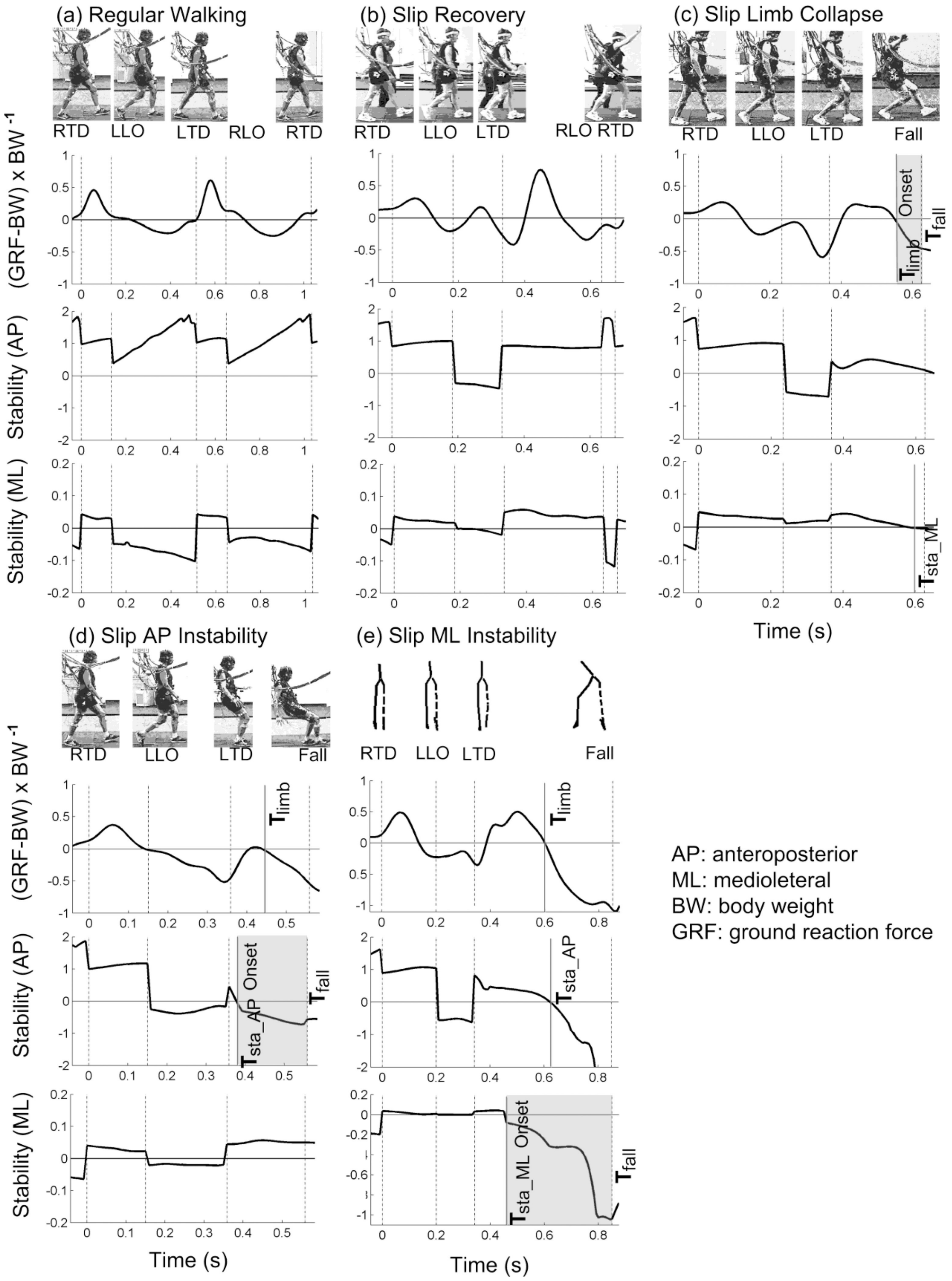

Figure 2.

Sample illustrations on how the time history of limb support (second panel) and stability [third for anteroposterior (AP) and bottom panel for mediolateral (ML)] measures were used to differentiate (a) regular walking, (b) a successful recovery following slip onset with falls (c-e). Limb support was measured as the difference between the ground reaction force (GRF) and the body weight (BW) normalized by BW [(GRF – BW) × BW^{-1}]. The zero (0) in stability (S) marks the limits of stability against backward loss of balance, whereas one marks the corresponding limits against forward loss of balance. In (a) regular walking or in (b)successful slip recovery, such trajectory flucturates between balance loss ($S < 0$) and stability recovery ($S > 0$), and between limb support waning (descending when $GRF - BW < 0$) or in its expanding (ascending when $GRF - BW > 0$). The solid vertical lines that bound shaded area mark the period from the *point-of-no-return* to the time of harness fall-arrest (Fall), either from (c, the same example as in Fig. 1a) limb collapse failure (T_{limb}), from (d) AP or from (e) ML instability failure (T_{sta_AP} or T_{sta_ML}, respectively). The dotted vertical lines indicate the timing of gait-slip events, such as leading (right) foot touchdown (RTD) and its liftoff (RLO) in (a) regular walking and (b) slip full recovery, or recovery foot (left) liftoff (LLO) and its touchdown (LTD). Slip onset followed immediately (~0.05 s) after RTD. When there were several failures in a trial (for instance, all three failures occurred in e), the *earliest* (failure in ML stability control in this case) was identified as the cause of fall. Still-frame video images of sagittal view as well as stick-figure recreation of frontal plane images were shown at the instant of RTD, LLO, LTD, RTD or at the onset of harness fall-arrest (Fall). The solid and dashed lines of the stick figures indicate the right and left sides, respectively.

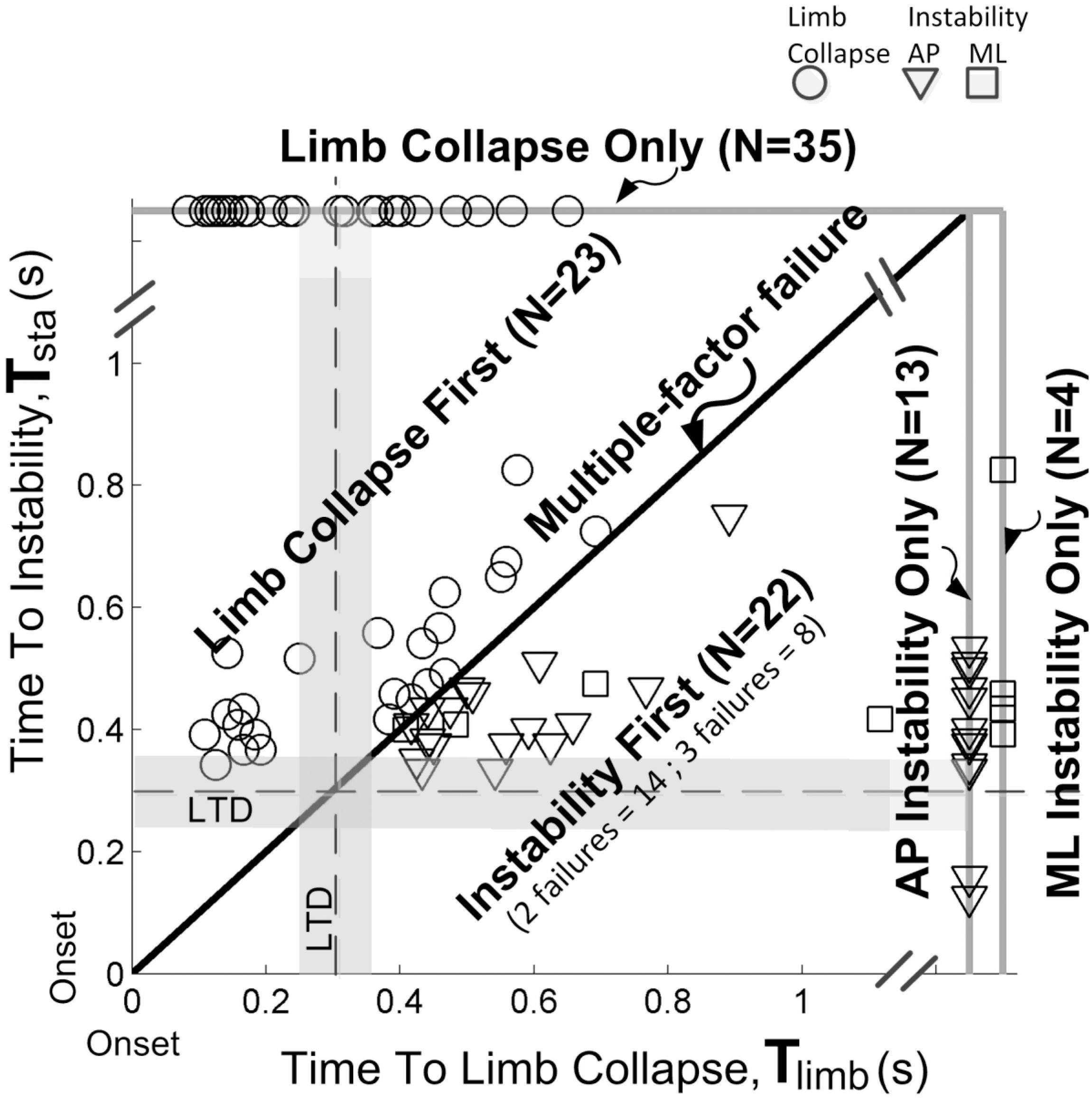

Figure 3.

The actual timing of the *point-of-no-return* for each failure reveals the cause of falls following 97 individual's novel slip exposure. For 45 individuals with *duo* or *triple* failures, the timing of their limb support failure and stability failure was reported in the abscissa and the ordinate, respectively. The thick diagonal (45°) line indicates the simultaneous occurrence of two or three failures (*i.e.,* the *multiple-factor* failure, N = 0). Above this line, falls resulted from the limb support failure (N = 23), which occurred earlier than the failure in stability recovery. Conversely, the failure in stability recovery all located below this diagonal line (N = 22). Notably, the remaining 35 of 58 limb collapse falls (60.3%) and 17 of 39 instability falls (42.5%) all resulted from *single* failure, displayed on the top and the right margin, respectively. The origin was set at the onset of the slip. The broken lines and the corresponding shaded areas indicate the group average and ± 1 standard deviation of the recovery foot (left) touchdown (LTD), respectively.

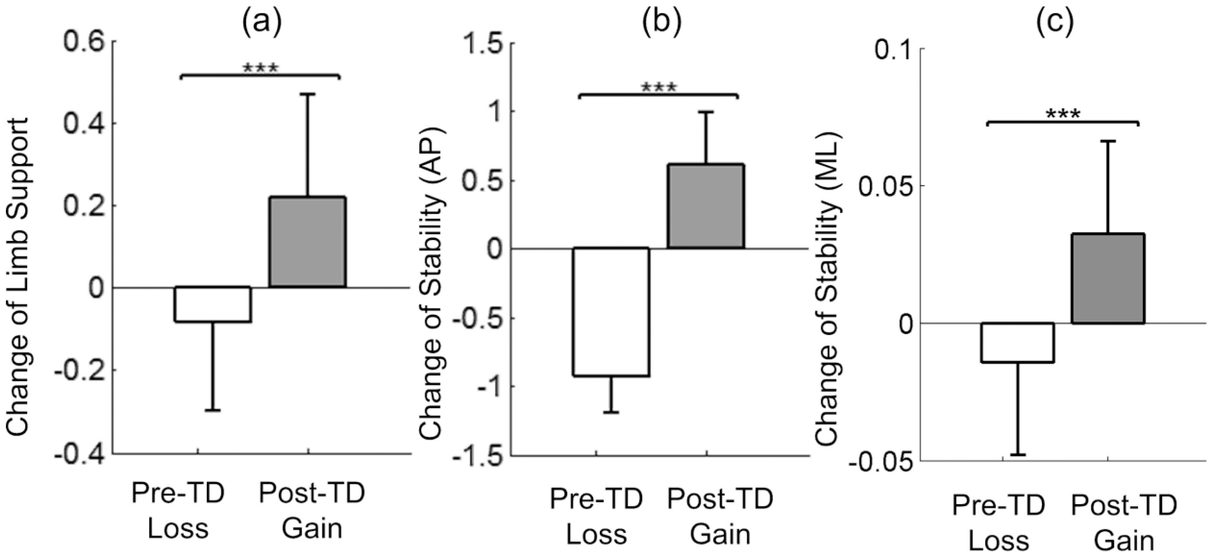

Figure 4.

The losses in (a) limb support, (b) AP stability and (c) ML stability control during the single stance phase from recovery foot (left) liftoff (LLO) to its pre-touchdown (pre-LTD = LTD - 10ms) and the gains in the three variables immediately after touchdown from pre-LTD to post-touchdown (post-LTD = LTD + 80ms). *** $p < 0.001$ for the paired t-tests between the magnitude of the losses and that of the gains.

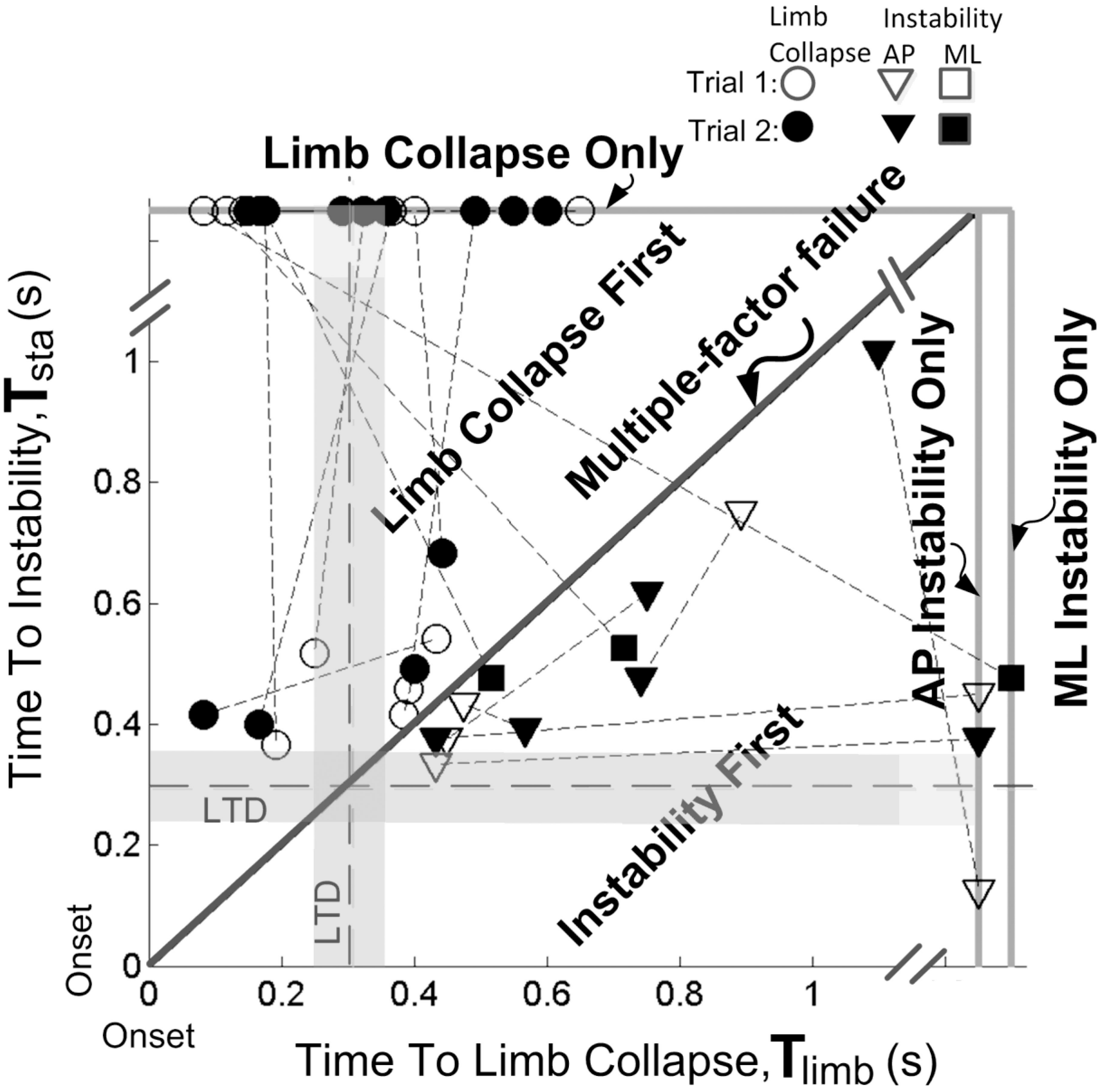

Figure 5.

Change in the causation of falls from the first to the second slip in 22 inidividuals, whose first-slip results was reported in Figure 3. The hollow markers indicate the first falls, and the filled ones indicate the second falls. Dotted lines connect the two falls of the same participant, and any dotted line crossing the threshold indicates the fall reason changed from the first fall to the second fall. The thick diagonal (45°) line indicates the simultaneous occurrence of two or three failures. Above this line, falls resulted from the limb support failure (N = 16 in first fall; N = 13 in second fall). Falls below the line resulted from the instability failure (N = 6 in first fall; N = 9 in second fall). The origin is set at the onset of the slip. The broken lines and the corresponding shaded areas indicate the group average and ± 1 standard deviation of the recovery foot (left) touchdown (LTD), respectively.

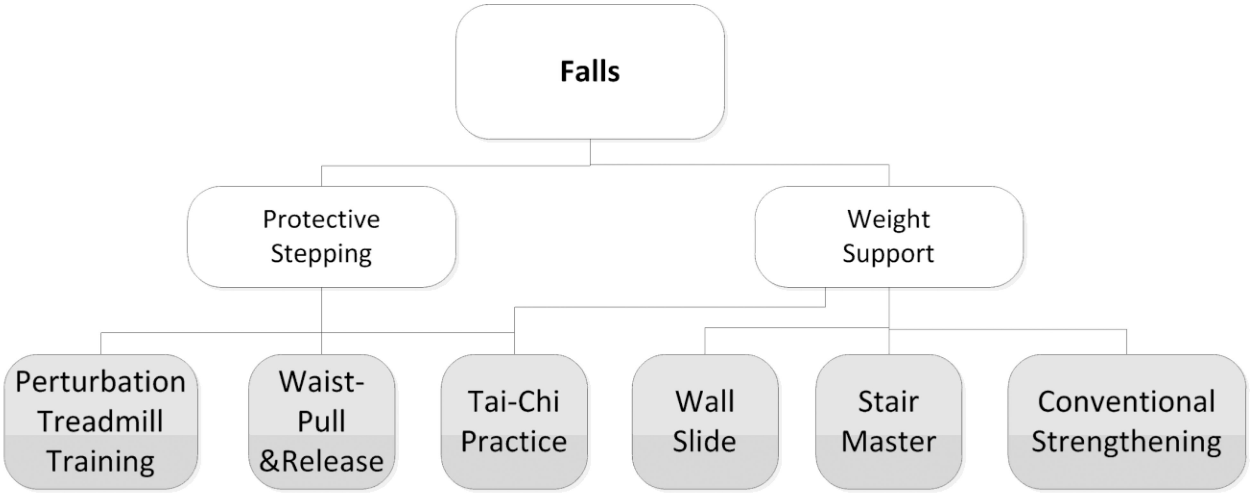

Figure 6.

Common and/or alternative fall prevention therapeutic approaches can be applied to address an individual’s vulnerability revealed by the fall causation assessment, whether the causation is one’s failure in providing adequate limb support or in the control of stability.

Table 1

Comparisons of the demographics in means ± SD between falls. Independent t-test and chi-square test were used.

	limb collapse (N = 58)	instability (N = 39)	P value
Age (year)	72.2 ± 5.5	71.6 ± 3.9	> 0.05 [a]
Male (%)	31	16	< 0.001 [b]
Body mass (kg)	79.4 ± 14.1	70.1 ± 12.8	0.001 [a]
Body height (cm)	163 ± 6	166 ± 8	> 0.05 [a]
BMI ($kg \times m^{-2}$)	30.1 ± 5.2	25.6 ± 4.7	< 0.001 [a]

[a] independent t-test

[b] chi-square test

Table 2

Causation of 22 repeated falls upon these participates' second slip. INS = instability; LC = limb collapse; AP = anteroposterior; ML = mediolateral. Shaded cells indicate the numbers of participates who had identical cause in the 1st and 2nd falls.

Trial / Causation			**1st Fall**		
			INS		**LC**
			AP	**ML**	
2nd Fall	INS	AP	6	0	0
		ML	0	0	3
	LC		0	0	13