Assessment of Fall Characteristics From Depth Sensor Videos

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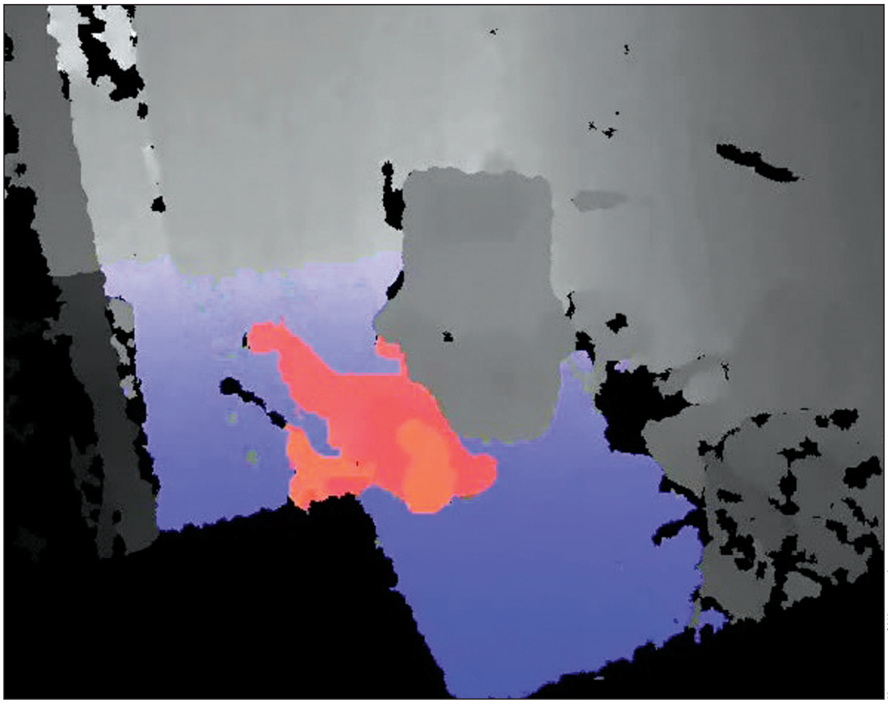
ABSTRACT

Falls are a major source of death and disability in older adults; little data, however, are available about the etiology of falls in community-dwelling older adults. Sensor systems installed in independent and assisted living residences of 105 older adults participating in an ongoing technology study were programmed to record live videos of probable fall events. Sixty-four fall video segments from 19 individuals were viewed and rated using the Falls Video Assessment Questionnaire. Raters identified that 56% (*n* = 36) of falls were due to an incorrect shift of body weight and 27% (*n* = 17) from losing support of an external object, such as an unlocked wheelchair or rolling walker. In 60% of falls, mobility aids were in the room or in use at the time of the fall. Use of environmentally embedded sensors provides a mechanism for real-time fall detection and, ultimately, may supply information to clinicians for fall prevention interventions. [*Journal of Gerontological Nursing, 43*(7), 13-19.]



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Falls are the primary source of nonfatal injury in older adults (Centers for Disease Control and Prevention [CDC] & National Center for Injury Prevention and Control, 2014). One in four older adults fall each year, but less than one half report the fall to a health care

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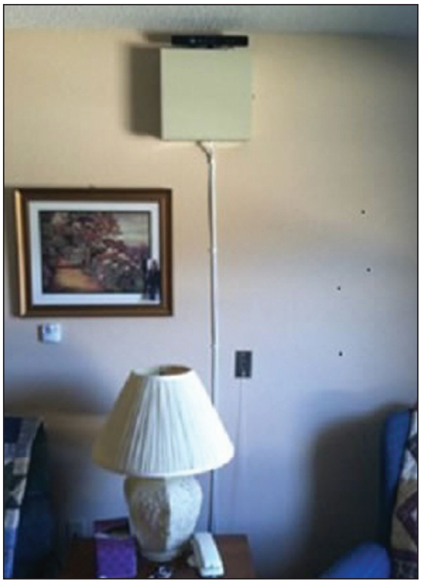

Figure 1. Depth sensor camera with a computer mounted on the wall in the main living area.

provider (CDC, 2016; Stevens et al., 2012). In 2012, direct medical costs of falls exceeded $34 billion (Burns, Stevens, & Lee, 2016). In addition to increased health care costs, falls can contribute to decreased quality of life and difficulties in self-care and activities of daily living (Hartholt et al., 2011). Because one half of all falls occur in the home environment (Schiller, Kramarow, & Dey, 2007), older adults who live alone are at risk for experiencing an unwitnessed fall, which may result in prolonged lying on the floor. Delayed treatment increases risks for hospitalization and subsequent moves to long-term care (LTC) facilities (Fleming & Brayne, 2008).

New technologies, such as environmental sensors, offer the opportunity to detect and signal falls at the time of the on-the-ground event. Environmentally embedded sensors such as webcams, radar, and depth camera systems may detect falls and alert caregivers that help may be needed (Phillips et al., 2016; Rantz et al., 2015; Rantz et al., 2014). In addition to fall detection, video sensors may provide insight into the mechanisms of falls that occur in the home, information that could inform future fall prevention efforts. Older adults are willing to live with technology that helps them maintain independence and do not find sensors intrusive when strategically positioned in their homes and identifying video is not recorded (Demiris, Parker Oliver, Giger, Skubic, & Rantz, 2009). At the University of Missouri, the interdisciplinary Center for Eldercare and Rehabilitation Technology (CERT) team has been developing and testing environmental sensor technologies in the laboratory and senior living communities since 2005 (Rantz et al., 2015).

A fall detection system, comprising an image-recording depth camera and computer to automatically process depth images, has been tested and in use since 2011 at TigerPlace, an Americare Systems, Inc. senior living community affiliated with the University of Missouri. TigerPlace is an aging-in-place community that accommodates varying levels of care needs by providing services aligned with specific individual needs (University of Missouri, 2016). TigerPlace residents may opt in or out of the aforementioned technology research. Depth sensor systems were initially trialed at TigerPlace, but have since been deployed in 12 assisted living facilities and two memory care facilities. The wall-mounted depth camera is strategically placed to provide a view of the main living area within individual apartments and the computer is housed in a nearby cabinet to process the video (**Figure 1**). Depth images are created using background subtraction to track moving bodies, separating them from stationary objects in the environment (Skubic et al., 2016). These depth images are processed as silhouettes to protect privacy. When an on-the-ground event is detected, the depth camera sensor system uses a decision tree to produce a percentage confidence that a fall occurred (Skubic et al., 2016). All depth-camera–recorded movements algorithmically classified as a potential fall are stored as brief video clips on a web-based secure server. The detection of potential falls generates alerts to CERT team members who then view the video and document their evaluation of the possible fall event.

Although fall events have been categorized as true falls or false alarms within the fall event database, there has been no further examination of the true fall videos. Therefore, the purpose of the current study was to identify characteristics of older adults' falls by viewing and rating depth image videos of fall events recorded by the fall detection system.

METHOD

Participants

The sample included 19 individuals who had sustained one or more falls from among 105 older adults residing at one of 15 senior housing sites participating in an ongoing technology study. The sample was primarily female (68%) and White (95%). Mean participant age was 84 (*SD* = 4.98 years), and 68% of fallers were ages 80 to 89. Seventy-nine percent were widowed or single, and 21% were married and living with their spouse. All research conducted by the CERT researchers was approved by the University of Missouri's Institutional Review Board and all research participants provided written informed consent.

Setting

Sensor systems were installed in TigerPlace and 14 Americare Systems, Inc. assisted living communities. Although floor plans of suites and apartments varied across these settings, depth cameras were consistently positioned in the main living area to visually capture the widest possible living expanse. Whenever the depth camera system detected a probable fall, on-site staff at TigerPlace or assisted living community staff received a prompt fall alert by e-mail.

Measures

The Fall Video Analysis Questionnaire (FVAQ) provided a framework to analyze the characteristics of falls. The FVAQ is a 24-item questionnaire that addresses the biomechanical, situational, behavioral, and environmental aspects of falls captured by the depth camera (Yang, Schonnop, Feldman, & Robinovitch, 2013). FVAQ items focused on three stages of falls: *initiation*, *descent*, and *impact*. The initiation stage items include the cause of the fall, activity at the time of the fall, and environmental factors present (e.g., mobility aids, clutter) (Yang et al., 2013). Initiation stage items also include whether the individual was falling from a height greater or lesser than standing height and if he or she was holding an object at the time of the fall. Descent stage factors included initial fall direction and whether the individual had a stepping response or reached out for items to try to stop or break the fall (Yang et al., 2013). The impact stage included body sites of greatest energy absorption and injury risk, landing configuration, and the impact to individual body parts (Yang et al., 2013).

The FVAQ was developed and validated using live video captures of falls in public areas of long-term care facilities (Yang et al., 2013). Yang et al. (2013) tested the reliability of the FVAQ using 221 video-captured falls. Teams of raters analyzed falls; 19 of 24 items showed agreement ≥80% and Cohen's kappa >0.60 (Yang et al., 2013). Intrarater reliability was reported as good in 18 of 24 questions with agreement of 89% and an average overall kappa of 0.69 (Yang et al., 2013). The current study is the first to use the FVAQ to categorize the characteristics of falls captured in private living areas and viewed in silhouette.

TABLE 1

FALL VIDEO ANALYSIS QUESTIONNAIRE ITEM RESPONSES WITH FREQUENCIES AND KAPPA RESULTS (*N* = 64)

Item/Response Option	*n* (%)	Kappa
Cause of fall		0.860
Incorrect transfer/shift of body weight	36 (56)	
Loss of support with external object	17 (27)	
Trip	8 (13)	
Bump	2 (3)	
Leg collapse, level of consciousness	1 (2)	
Slip	0	
Activity at time of fall		0.909
Walking	26 (41)	
Standing	23 (36)	
Transfer from standing	7 (11)	
Transfer from sitting or lying position	6 (9)	
Seated	2 (3)	
Mobility aids		0.936
None visible	23 (36)	
Wheelchair in use	13 (20)	
Walker in use	13 (20)	
Wheelchair visible (not in use)	9 (14)	
Walker visible (not in use)	4 (6)	
Cane in use	2 (3)	
Cane visible (not in use)	0	
Crutch in use	0	
Crutch visible (not in use)	0	
Held objects		0.895
Yes	34 (53)	
No	30 (47)	
Height of fall		0.956
Standing height	50 (78)	
Lower than standing height	14 (22)	
Greater than standing height	0	
Contribution of clutter		0.950
No	54 (84)	
Yes	10 (16)	

Data Collection

Raters viewed 10-second video recordings of probable fall events stored on a secure server that occurred between May 2015 and June 2016. Sixty-four fall videos were included in the analysis. Thirty falls recorded belonged to one individual, although most individuals had between one and three falls over the 13-month period included in the study. Of the 18 remaining individuals, 12 had one fall, one had two falls, three had three falls, one had four falls, and one had six falls.

TABLE 1 (CONTINUED)

FALL VIDEO ANALYSIS QUESTIONNAIRE ITEM RESPONSES WITH FREQUENCIES AND KAPPA RESULTS ($N = 64$)

Item/Response Option	*n* (%)	Kappa
Initial fall direction		0.929
Primarily sideways	34 (53)	
Primarily backward	24 (38)	
Primarily forward	5 (8)	
Straight down	1 (1)	
Stepping responses		0.943
No	36 (56)	
Yes	28 (44)	
Reach-to-grasp		1.000
Yes	34 (53)	
No	30 (47)	
Landing configuration		1.000
Primarily backward	31 (48)	
Primarily sideways	29 (45)	
Primarily forward	4 (6)	
Site of greatest energy absorption		1.000
Pelvis/torso/buttocks	52 (81)	
Lower limb	6 (9)	
Upper limb	3 (5)	
Head	3 (5)	
Site of greatest injury risk/impact severity		1.000
Pelvis/torso/buttocks	46 (72)	
Head	11 (17)	
Upper limb	4 (6)	
Lower limb	3 (5)	
Impact site		
Pelvis	63 (98)	0.859
Torso	61 (95)	0.660
Elbow/forearm	52 (81)	0.961
Shoulder	47 (73)	1.000
Hand/wrist	43 (67)	0.849
Head	42 (66)	0.953
Knee	18 (28)	0.967

Interrater Reliability Process

As a first step in rater training and to establish interrater reliability, four authors, two of whom were doctoral students (J.J.O., B.F.) and two of whom were CERT faculty (L.J.P., G.L.A.), scored 10 fall video clips using the FVAQ. During the initial scoring exercise, it was determined that several FVAQ items that required identification of specific environmental features, such as floor material, floor conditions (either wet or dry and transitions in material, color, pattern, or texture), and lighting conditions, could not be scored because depth camera recordings were processed as silhouettes to protect privacy. Thus, fall video clips were rated using 19 of the 24 FVAQ items. The four authors reviewed discrepant ratings and, through repeated viewing of video clips and discussion, came to consensus on all FVAQ items for the first 10 videos.

Next, two raters (J.J.O., B.F.) independently rated 30 new videos, after which kappa coefficient values were obtained using SPSS version 23 for the selected 19 FVAQ items. Initial kappa results were low, with good agreement in only three of the 19 questions. Raters met and came to consensus on discrepant item ratings using the same process as the first 10 videos that is described above. This process was repeated for the remaining 24 videos, resulting in a total of 64 video clips rated with the FVAQ.

RESULTS

Interrater Reliability

After discussion and multiple viewings of each video, agreement was reached on most FVAQ items. Final kappa results indicating agreement on each of the 19 items ranged from 0.66 to 1.00 (**Table 1**). A kappa result >0.61 is considered substantial agreement (Viera & Garrett, 2005). Eighteen of the 19 items were >0.84, indicating almost perfect agreement (Viera & Garrett, 2005). Only a few areas of disagreement remained and each particular item was disagreed upon between one and four times for the 64 falls (**Table 2**). Approximately one half (43%) of discrepant ratings originated from disagreement in fall impact to a specific body part: head, pelvis, torso, hand, or elbow. Hand/wrist impact was the single item with most disagreement (4 of 64).

Characteristics of Falls

Each of the 64 falls were analyzed using the FVAQ. **Table 1** provides the distribution of individual FVAQ item ratings.

Initiation Stage. More than 50% (n = 36) of the 64 falls occurred due to an incorrect transfer or shift of body weight. Individuals moved their body beyond their centers of gravity, usually while walking (n = 26) or standing (n = 23). Fewer fell from transfers while standing (n = 7) or sitting or lying down (n = 6). Twenty-seven percent (n = 17) of falls occurred from a loss of support from an external object such as an unlocked wheelchair, rolling beside table, or folding chair. Less frequent were *trips* (n = 8), defined as impact with an object by the shin or foot, and *bumps* (n = 2), defined as impact with an object above the knee. Slips, a common cause of falls, did not occur in any of the 64 falls.

Mobility aids, such as wheelchairs, canes, and walkers, were in the room but not in use in 20% of falls (n = 13). Mobility aids were in use at the time of the fall in 40% of cases (n = 26). Anecdotally, raters noted that mobility aids were not being used appropriately during some fall events, but the FVAQ does not include an item addressing correct use of mobility aids. For example, a wheelchair may be unlocked or dragged behind the individual or a walker may be pulled along off to the side of the faller while ambulating.

During more than one half (n = 34) of falls, fallers had an object in their hand other than a mobility aid. In 50 falls (78%), the descent distance of the fall was standing height (i.e., the faller fell from a standing position to the floor). The other falls were lower than standing height, with falls occurring from a sitting or crouched position. None of the falls were at greater than standing height. Possible examples of a fall from greater than standing height are falls down a flight of stairs or off a raised platform. Clutter was a contributor to the fall only 16% of the time (n = 10).

TABLE 2

FALL VIDEO ANALYSIS QUESTIONNAIRE (FVAQ) ITEM DISAGREEMENT BETWEEN RATERS

FVAQ Item	Frequency of Disagreements (n)
Cause of fall	2
Activity at time of fall	1
Mobility aids	0
Held objects	2
Height of fall	0
Contribution of clutter	3
Initial fall direction	1
Stepping responses	0
Reach-to-grasp	2
Final landing configuration	2
Site of greatest energy absorption	0
Site of greatest perceived injury risk	0
Head impact	1
Pelvis impact	1
Torso impact	1
Hand/wrist impact	4
Elbow/forearm impact	1
Knee impact	0
Shoulder impact	0
Total	21

Descent Stage. The descent stage includes the initial fall direction, stepping responses, and reach-to-grasp responses. In 53% of falls (n = 34), fallers initially fell sideways. Backwards falls occurred 38% of the time (n = 24). *Stepping responses* are defined as individuals trying to avert the fall and retain their balance by taking extra steps. These stepping responses occurred 44% (n = 28) of the time. In 53% of falls (n = 34), fallers had reach-to-grasp responses, trying to stop or break the fall by reaching for nearby objects.

Impact Stage. The landing configuration of 48% (n = 31) of falls was backward, meaning the faller landed mostly on his/her back or pelvis. Approximately 45% (n = 29) of fallers landed on their side. The pelvis/buttocks/torso area absorbed the greatest amount of energy in 81% (n = 52) of falls and was at the greatest risk of injury in 72% (n = 46) of falls. Impact to the pelvis and torso were the most common, occurring in 98% (n = 63) and 95% (n = 61) of falls, respectively. The next most frequent areas of impact were the elbow/forearm and shoulder in 81% (n = 52) and 73% (n = 47) of fall incidents, respectively. Hand/wrist area impact occurred in 67% (n = 43) of falls. The head received impact in 66% (n = 42) of falls. Knee impact was the least common at 28% (n = 18). **Figure 2** depicts the three stages of an actual fall analyzed in the current study.

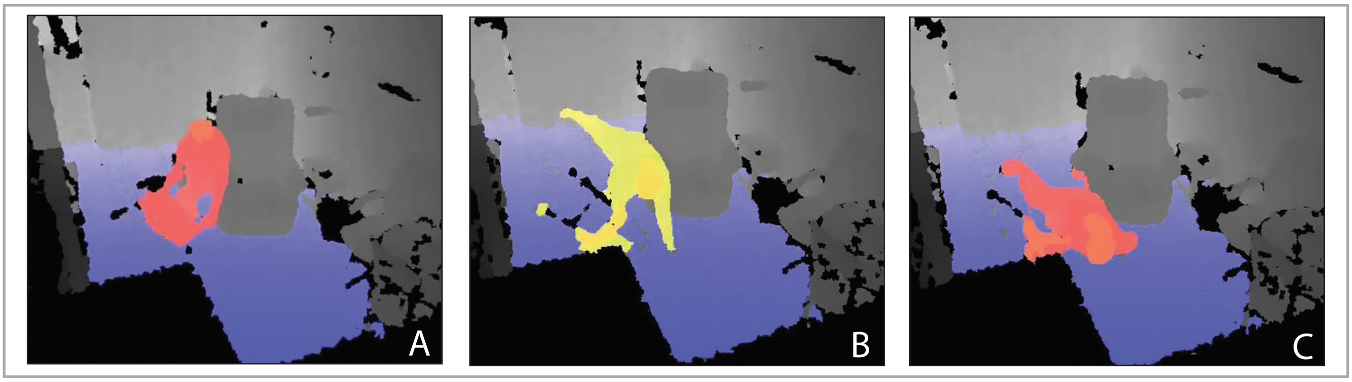

Figure 2. Depth camera images of the three stages of a fall: (A) initiation, (B) descent, and (C) impact. The faller (with walker) appears in contrasting colors in the center of the images.

DISCUSSION

The current study identified characteristics of older adults' falls by viewing and rating depth image videos of fall events recorded by the fall detection system. Capturing falls real-time facilitates observation of contributing factors and processes of falls rather than relying on historical reports that are often inaccurate (Yang, Feldman, Leung, Scott, & Robinovitch, 2015). Falls were most commonly attributed to an imbalance or incorrect shift of body weight. Slips and trips occurred rarely in this sample, but have been reported in one third of hospital inpatient falls (Potter et al., 2016). Because all apartment areas in view of the depth camera were carpeted, slips on slick flooring would not be possible. Clutter was a factor in only 16% of falls.

A key observation in the current study was the frequency with which falls occurred due to the loss of support from an external object. Approximately one third of the observed falls involved presumably unlocked wheelchairs, wheeled overbed tables, folding chairs, and the improper use of mobility aids. In 60% of falls, mobility aids were in the room or in use at the time of the fall. Clinicians had identified the need for mobility aids in these individuals, but the aids may not have been used or may have been used incorrectly. In 20% of falls, a walker or wheelchair was in the room, but was not being used. These findings illustrate the importance of educating older adults on the correct use of mobility aids, as well as on the risk of falling when mobility aids are not used properly.

Consistent with prior research, most individuals fell sideways; sideways fallers are at highest risk for hip fracture (Hayes et al., 1996). The current authors' interpretations from recordings of privacy-preserving depth images about cause of fall, activity at time of fall, and mobility aids concur with Yang et al.'s (2015) video recordings in long-term care facilities. For example, in the current study, the cause of the fall was attributed to incorrect transfer in 56% of cases and Yang et al. (2015) found incorrect transfer to be the cause in 47% of cases. Similar to Yang et al.'s (2015) finding that walking was the most common activity at the time of a fall (44.2%) and wheelchairs were used in 17% of cases, the current authors found 41% of falls rated involved walking and 20% involved wheelchair use. These findings provide evidence that fall causes and circumstances can be accurately gleaned from depth sensor images.

The current study addresses a limitation of other studies: characteristics of falls captured in common areas of residential facilities may differ from those in private living areas (Yang et al., 2015). Differences are apparent. Contrary to Yang et al.'s (2015) findings of loss of support with an external object as causation in 16% of falls, the current study's findings indicate loss of support 27% of the time. No mobility aid was in use in 69% of common area falls (Yang et al., 2015), but was in 56% of the current sample.

LIMITATIONS

First, although fall videos were recorded on 19 individuals, approximately one half of the videos came from one individual. Consequently, characteristics of falls from the individual with multiple falls may have been repeatedly observed. Therefore, each fall video was viewed and rated independent of the other fall videos.

Second, the shadow nature of the videos makes it difficult to determine exactly what is happening before, during, and after the fall. Depth-image camera videos do not allow for precise visualization of all body areas and views may be obscured if specific body parts sustained impact out of camera range or behind a piece of furniture. Determining pre-fall activity can be challenging with only a few seconds of video recorded before the fall occurred. Given Robinovitch et al.'s (2013) recommendation to view 60 seconds of footage before and after a fall, having only 10 seconds of video footage limited the current analysis.

Third, in the current study, the depth camera was positioned only in the main living area, purposely avoiding the bedroom and bathroom areas to respect privacy concerns. Thus, if a fall occurred in these rooms, the depth camera did not detect the event. In addition, some falls occurred outside the limited visual range of the camera and raters were unable to analyze them.

IMPLICATIONS

Future research should expand the use of sensor technology to better understand how falls occur. As the depth camera technology improves (Banerjee, Keller, Popescu, & Skubic, 2015), body images will be sharper without sacrificing privacy. Sharper images will yield greater detail at the time of the fall, which could help clinicians individualize interventions that address specific fall circumstances.

CONCLUSION

Use of environmentally embedded sensors provides a mechanism for real-time fall detection and, ultimately, may supply evidence on which clinicians can base fall prevention interventions. As in-home sensor technology becomes more widespread, fewer falls will go unwitnessed, yielding a stronger evidence base for fall prevention interventions.

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