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FALL DETECTION AND PREVENTION FOR THE ELDERLY: A REVIEW OF TRENDS AND CHALLENGES

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Abstract— It is of little surprise that falling is often accepted as a natural part of the aging process. In fact, it is the impact rather than the occurrence of falls in the elderly, which is of most concern. Aging people are typically frailer, more unsteady, and have slower reactions, thus are more likely to fall and be injured than younger individuals. Typically, research and industry presented various practical solutions for assisting the elderly and their caregivers against falls via detecting falls and triggering notification alarms calling for help as soon as falls occur in order to diminish fall consequences. Furthermore, fall likelihood prediction systems have been emerged lately based on the manipulation of the medical and behavioral history of elderly patients in order to predict the possibility of falls occurrence. Accordingly, response from caregivers may be triggered prior to most fall occurrences and accordingly prevent falls from taking place. This paper presents an extensive review for the state-of-the-art trends and technologies of fall detection and prevention systems assisting the elderly people and their caregivers. Furthermore, this paper discusses the main challenges, facing elderly fall prevention, along with suggestions for future research directions.

Keywords— Fall detection, fall prevention, elderly monitoring, motion sensing

I. INTRODUCTION

In around 35 years and by 2050, it's estimated that more than one in each group of five people will be aged 65 or over. In this age group, falling is one of the most serious life-threatening events that can occur, as approximately one-third to one-half of the population aged 65 and over (mostly aging care centres residents) experience falls on a yearly basis and half of these elderly do fall repeatedly .So, the automatic detection of falls would help reducing the time of arrival of medical caregiver, and accordingly reducing the mortality rate . Falls are the leading cause of injury in elderly people and the leading cause of accidental death in those 75 years of age and older . Also, more than 90% of hip fractures occur as a result of falls in persons aged 70 years and over .Falls not only cause physical injury such as many disabling fractures; they also have dramatic psychological, medical and social consequences. The emerging picture is that falls are not a rare occurrence among older persons.

The rest of this paper is organized as follows. Section II discusses causes and consequences of elderly falls. Section III reviews the major research work done recently in the area of elderly monitoring as well as fall detection and prevention. Several categories of modern commercial sensor devices assisting the elderly and their caregivers for detecting and preventing falls and consequent injuries are presented in section IV. Finally, section V concludes the paper and discusses the main challenges facing research and development in the field of elderly fall prevention along with recommendations and suggestions for future research directions.

II. CAUSES AND CONSEQUENCES OF ELDERLY FALLS

Falling among the elderly happens due to different causes as well as it leads to different consequences. Being aware of those reasons and consequences serves researchers, designers, and developers of fall detection and prevention systems to develop various creative solutions for the problem of elderly falls.

A. Causes

There are several reasons why elderly fall. Some reasons; such as age, gender, being unconscious, or suffering from chronic neurological or mental problems, cannot be controlled. Whereas other causes; such as medications side effects, insufficient vision, poor hearing, or muscle weakness can be controlled or modified. Figure 1 classifies the most common reasons causing falls in the elderly according to their origin and controllability.

The presence of more than one cause of falling is common, and several studies have shown that the risk of falling increases dramatically as the number of causes increases. Several studies classify the factors associated with falls/causes of falls as extrinsic/environmental and intrinsic/personal. Environmental factors, which refer to factors originating from the patient's surrounding/external environment such as, loose carpets, wet or slippery floors, poorly constructed steps, etc. These factors cause falls in the local setting.

On the other hand, considering the fact that the leading causes of injury and mortality for elderly people are no longer infectious in nature, personal factors appear to also contribute to increase risk of falling. Intrinsic or personal factors, which relate to age-associated physiological and neurological functions changes, medications (such as: antidepressants or sedatives), as well as diseases (such as: hypertension, osteoarthritis, diabetes and sensory impairment, Alzheimer's disease or other forms of dementia, etc.), represent factors related to co-morbid conditions and reflect the rise and predominance of chronic diseases and accordingly the rise of elderly falls rate due to these diseases.

B. Consequences

- The average length of hospital stay is more than twice, as long in each age group for falls, for different causes of hospitalization for people over the age of 65. Falls among the elderly is increasingly being recognized as an issue of concern in all types of countries whether developed or developing countries . Any individual, especially if an aging person, can be negatively affected in various ways as a result of falling. Even a small fall can profoundly affect the health of elderly people. Yet, in this population, falls continue to be a predominant cause of loss of functioning and death. Falls in the elderly may precipitate adverse physical, psychological, social, financial and medical, as well as governmental and community consequences. Figure 2 shows the main consequences related to elderly falling.

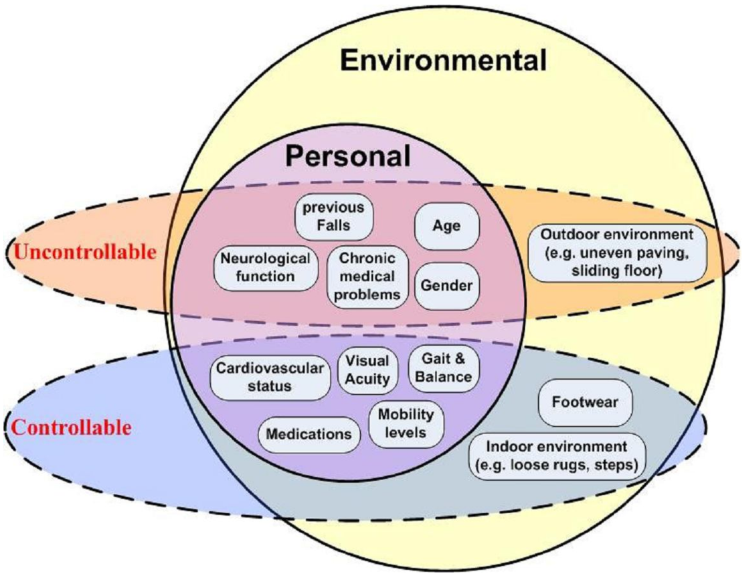

Figure 1. Categories of common reasons causing falls

- **Physical consequences**: are represented in possible injury i.e. broken bone or soft tissue injury, pain and discomfort, reduced mobility and possible long-term disability, and most of the time lead to increase the loss of independence and the ability to look after himself/herself.

- **Psychological consequences**: lead to loss of confidence when walking and moving due to the increased fear of repeated falling, fear and anxiety, in addition to distress, and embarrassment.

- Social consequences: are represented in curtailment of possible routine social activities, loss of independence and a reliance on family, friends or possible move into aging residential or nursing care center.

- **Financial and medical consequences**: signify the direct costs of medical care associated with injuries represented in increased costs to the statutory services such as physiotherapy rehabilitation, hospital care, and social care. Also, the immediate impact and consequences from the falls seen in health center were laceration (sometimes resulted in tissue damage) needing cleaning and dressing. For some patients, the wounds resulted in difficult to heal, chronic leg ulcers requiring frequent cleaning and dressing at the health center .

- **Governmental and community consequences**: indicate the fact that falls can have devastating effects on people's health and that falls greatly contribute to the level of hospital admissions and health insurance costs. So, from that point, governments may work hard to improve both the prevention and treatment of falls and these are most effective when social care and the government work together putting in place the legal conditions and financial incentives to drive such integration. Also, another fact is that as the population gets older, it has to be recognized that community health and social care organizations need to work more closely to set up effective falls prevention programs and to consider this as even more of a priority. That is, for little initial investment patients are getting better care, more falls are being prevented, and money is being saved. Generally, a concerted drive from the national to the local level in order to work for tackling elderly falls has to be adopted and activated in order to get organizations across health, social care, and local community authorities working together.

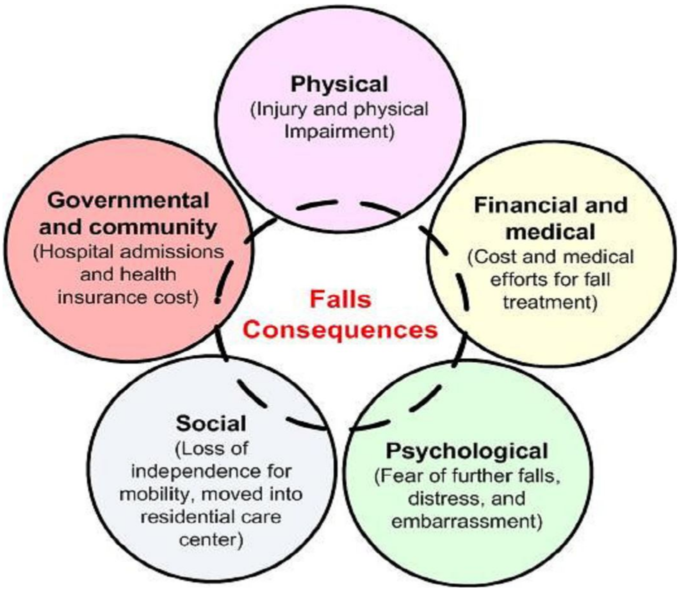

Figure 2. The main consequences related to elderly falling

III. REVIEW OF LITERATURE

There has been significant interest in falls both from a research and commercial perspective for many years. A variety of approaches have been taken technologically towards falls detection with varying degrees of accuracy. A number of attempts have been made to monitor not only falls, but also to generally monitor daily activities without attaching devices to the body, then to prevent falls accordingly.

On the other hand, many approaches for using accelerometry to detect falls were proposed. In those approaches, a change in body orientation from upright to lying that occurs immediately after a large negative acceleration indicates a fall. However, generally despite all the research dedicated to fall detection, there still isn't a 100% reliable algorithm that catches all falls with no false alarms. Furthermore, a limited number of research works has been conducted concerning the scope of fall prediction via monitoring and modeling patients' behavior in order to take protective actions that prevent falls occurrence. This section presents a detailed review of research work achieved in order to highlight various solutions proposed for tackling the problem of fall detection and prevention from different perspectives. Table 1, summarizes the proposed fall detection approaches, the contributions, and the drawbacks/challenges for each research work surveyed in this review.

Authors designed and created a fall detection system for the elderly as a wearable monitoring device, distinguishing between fall and non-fall events, which can link wirelessly with a pre-programmed laptop computer or Bluetooth-compatible mobile phone. Upon detecting a fall, the device communicates wirelessly with the laptop/cell phone to call emergency contacts. The device also detects abnormal tilt and warns the user to correct their posture to minimize the risk of falling. Moreover, in addition to the visual alert (flashing LED) fall alert, the proposed fall detection device has audio (siren) and tactile (vibrating buzzer) alert options for the seeing/hearing-impaired people and facilitates a manual cancel button in the event of a false alarm or falls that can be recovered by the user. Regarding the performance assessment of the proposed device, some actions have not been successfully distinguished, by one of the proposed algorithms, to be falls or non-falls.

Generally, many authors proposed approaches for capturing images of people and then detect visual fall based on image processing techniques. However, such approaches still having challenges and limitations on pervasive detection affordability and acceptability. That's due to many reasons such as the detection area is limited within monitoring environment, which is costly to build up. Also, the people's privacy is compromised. Moreover, visual fall detection is inherently prone to high levels of false positive (a fall might not be a real fall, but a deliberate movement towards the ground) as most of current systems are unable to 100% discriminate between context-base events such as real fall incident and an event when person is lying or sitting down abruptly. Furthermore, existent fall detection systems tend to deal with restricted movement patterns and limited normal scenarios like walking; however in real indoor environments various normal /abnormal motions occur.

Table 1: A summary of the surveyed fall detection research work

Reference	Proposed approach	Contributions	Challenges
[7]	*PerFallD*: A Pervasive Fall Detection system using mobile phones	Uses Android G1 phone mobile platform to conduct fall detection, the system automatically and iteratively calls and/or texts emergency contacts according to priorities on fall detection, available in both indoor and outdoor environment	Mobile phones limited battery and affordability, false alarms, integrating the system with some extra protection devices, e.g., airbag to reduce fall impacts
[12]	Wearable fall detection monitoring system for the elderly	Distinguishes between fall and non-fall events, provides visual, audio, and tactile fall alerts	Some actions have not been successfully distinguished to be falls/non-falls, as a wearable device, old people tend to forget wearing it, produces false alarms
[13]	Wearable fall detection monitoring system based on TEMPO 3.0 sensor nodes [14]	Applies both tri-axial accelerometers and gyroscopes, improves fall detection accuracy, reduces both false positive and false negative alarms	Facing difficulties in differentiating actions that need context information
[15]	*WAMAS*: Wearable Accelerometric Motion Analysis System	Measures head motion via 3-axis sensors attached to both corners of eyeglass frames and two more above the hips at the waist, warns the wearer of pre-fall behavior	As a wearable device, old people tend to forget wearing it, needs lighter weight, digital input, voice output improvements
[16]	*SPEEDY*: a wrist wearable watch-like fall detector	Easy to wear, smaller than the system proposed in [15], analyzing walking activity	The complexity of the fall detection algorithm, not all fall situations are detected with the same certainty, as a wearable device, old people tend to forget wearing it
[25]	A hierarchical-based architecture for healthcare monitoring applications in Wireless Heterogeneous Networks.	Wearable (built into a fabric belt) sensor systems, environmental sensor network for outdoor elderly/chronic-patients monitoring, group-based monitoring and assistance, adaptive security factors for data transmission	Fabric-belt wearable sensor system, performance issues of Bluetooth security and polynomial-based encryption
[26]	Collaborative multi-sensors based system for adaptive body posture analysis	Collaborative sensors based detection of body behavior modes and accidental falling incidents, adaptive	Sensors distributed over the body that transmit positions, cannot correctly determine the situation of body after

		adjustment model to detect elderly body postures	collision, applying additional gyroscope sensors to reconstruct the falling situations
[27]	Vision-based fall detection system for the elderly	Models human motion and audio track of the video using HMMs, avoids false alarms via using the impact sound of a falling person	Hard to estimate moving object trajectories, inaccurate detection depending on the relative position of the person and camera, occluding objects, requires using omnidirectional camera

IV. FALL DETECTION AND PREVENTION COMMERCIAL SOLUTIONS

Recently, the number of proposed fall-detection systems developed has increased dramatically. In an aging society, the elderly can be monitored with numerous physiological, physical, and passive devices.

Many monitoring and fall prevention commercial products are now available in the market, each with its pros and cons. Sensors can be installed in the elderly wearable or hand-held device or even in elderly resident room at home or health care facility for continuous mobility assistance and unobtrusive fall prevention. In the last years, there have been many commercial solutions aimed at automatic and non-automatic detection of falls such as the wearable fall detectors that are based on combinations of accelerometers and tilt sensors.

Also, several products, attempting to address the problem of fall detection and help elderly people requesting help when fall, are already existed on the market and have reached commercialization .Most of the already available products provide pendant or wristband help button in order for the patient to be able to call for help when fall and become totally helpless.

Figure 3 depicts pendant and wristband help button facilities. Critical problems are associated with those solutions like non-automatic buttons is often unreachable after the fall and old people tend to forget wearing them frequently . Moreover, most automatic wearable devices produce many false alarms.

Other hand-held, movement-sensing, and anti-wondering solutions have been proposed with their own contributions as well as having several drawbacks facing each of them. This section presents and summarizes several modern commercial sensors and research approaches and prototypes, which tend to improve the quality of life and assist the elderly and their caregivers for preventing falls and consequent injuries in the elderly.

A. Wearable and hand-held solutions

Many proposed approaches, based on the technology of accelerometers and gyroscopes, have been proposed for tackling the fall detection and prevention issue. The accelerometer is a device that can detect the magnitude and direction of acceleration along a certain axis .

Figure 3. Pendant and wristband help buttons

Using tri-axial accelerometers with applying thresholds, is one of the most common and simple methodology for objectively monitoring a range of human movements as well as fall detection.

So, any motion that exceeds some threshold value of acceleration will be considered a fall. As when a person falls, their orientation often changes from vertically standing to horizontally lying on the floor. Hence, analyzing post-fall orientation, in addition to acceleration threshold, is an important approach to be considered. Also, taking the dot product or cross product of the axial accelerations to obtain the cross product magnitude and angle change is considered as more advanced fall detection approach. Researchers generally agree that optimal fall sensor placement on the body is at the waist. The gyroscope, which is a device measures orientation, consists of a spinning wheel whose axle is free to take any orientation . Like an accelerometer gyroscope can measure the orientation along one or multiple axes.

Using gyroscopes with a similarly-placed gyroscope that measures pitch and roll angular velocities with applying a threshold algorithm to angular change, velocity, and acceleration, can be successful in fall and tilt detection .

B. Movement-sensing solutions

On the other hand, concerning the commercialized fall monitoring and prevention products, another classification is to categorize products into movement-sensing monitoring solutions and anti-wandering solutions. Figure 5 summarizes the main products under each category that will be further discussed in more details.

B.i Weight-sensitive reverse pressure pads :

For bed, chair, and toilet fall monitoring, there are weight-sensitive reverse pressure pads. When connected to a fall/mobility monitor, the pressure pad will trigger the monitor, or the wireless transmitter if using a wireless system monitor, when weight is removed from the pressure pad.

When a wireless system monitor is used, it sends a signal to the central monitor unit informing the caregiver of the activated reverse pressure pad. Most of the time, an optional wireless alarm light is also available for this system. The main drawbacks of reverse pressure pads based fall monitoring systems are related to maintenance issues, where it's not advisable to fold or immerse pressure pads in any solutions and they should be wipe-cleaned only by using disinfectant wipes or anti-bacterial cleaner, in addition to the cost of frequent replacing for pads when the warranty period expires .Figure 6 shows an example of weight-sensitive reverse pressure pads.

B.ii Wheelchair/bed pull-string monitor :

The pull-string fall monitor attaching a string to patient clothing which alerts caregivers when the patient tries to get up. It features a magnet-positioned cord, so when the resident attempts to get out of their chair, the tension on the pull string cord causes the magnet to pull away from its position, causing the fall alarm to sound, alerting the caregiver of the resident's departure. Adjust the cord stop to the desired pull-string length for the resident's comfort and also to prevent false alarms .

B.iii Non-restraint wheelchair seat-belts :

These wheelchair seat-belts are available in two types, namely Easy-Release-Buckle and Quick-Release-Hook and Loop wheelchair seat-belts. Both types of wheelchair seat-belts are not designed to restrain or hold individuals in position in their chairs, whereas to reduce falls by triggering a fall monitor mounted to the chair to signal a caregiver pager when the easy release buckle is unbuckled or the Hook and Loop strap is opened and inform the caregiver of which resident's seatbelt was opened. Wheelchair seat-belts can also be set up as a wireless fall monitoring system that trigger the wireless system to signal a caregiver pager directly with no central monitor required. Moreover, an optional wireless alarm light is also available for this system. The main drawback of wheelchair seat-belts based fall monitoring is the limited applicability to wheelchairs only.

C. Anti-wandering solutions

C.i Door alarm bars:

The function of the anti-wandering door alarm system is based on two components, namely the door alarm bar and the resident's wristband. So, when the resident hangs the door alarm bar, attempting to wander too close or through the exit or doorway in the care facility, this will act like plugging the resident's wristband in door alarm bar. Accordingly, the door alarm sounds audibly and visually.

C.ii Weight-sensing floor mats :

This fall monitoring system is based on sensing floor mats that alarm when stepped on. Weight sensing floor mats, which may be placed at the side of a bed, hallway or in a doorway, trigger fall monitors, central monitors or caregiver pagers to alert when weight is placed on the floor mat meaning that a resident arises or attempts to depart. So, on the contrary of the reverse pressure pad that activates when weight is removed from it, weight-sensitive pressure floor mats are weight-sensitive floor coverings that activate when stepped on. The available weight-sensing floor mats can be configured in three different ways; cordless with wireless transmitter fall monitor, corded with wireless transmitter fall monitor, and corded with corded local fall monitor floor mats. The first type works wirelessly with central monitors and caregiver pagers with no cords to trip on with cordless products, and caregivers may freely place them in the bedside or doorways. The second type wirelessly signals a caregiver pager and/or the central monitor allowing caregiver paging directly from the floor mat with no central monitor required and an optional wireless alarm light is also available for this system. The third type provides a configuration where the floor mat plugs directly into the fall monitor .

The main drawback of the weight-sensing floor mats based fall monitoring is that they are effective in detecting movement over ground-area where they are placed, however they may be suited as one component of a more comprehensive fall prevention monitoring system in conjunction with other measures such as other motion sensors/detectors, like ultrasound, passive infrared (PIR) sensing units, etc.

An example of the anti-wandering wristband based door alarm system

C.iii Anti-wandering wireless motion sensors/detectors:
(1) Wireless passive infrared (PIR) fall alarm monitor: The PIR sensor, which is used as ‖motion detector‖, is a compact fall monitor that has a detecting area to report movement when the passive infrared field is interrupted. When positioned along the bedside the fall monitor will alarm as the resident attempts to vacate the bed. When positioned by a door the fall monitor will alarm as the resident approaches the doorway, which may help to prevent the resident from moving and accordingly falling.

(2) Wireless fall alarm monitor, receiver, and pager: Another type of PIR motion detectors, which provides noise reduction in health care centers by moving the alarm noise outside of the room via having a detecting area of the fall monitor to report movement when the passive infrared field is interrupted. The first way to achieve moving the alarm noise outside of the room this is that instead of sounding at the motion sensor itself, the motion sensor sends a wireless signal to the receiver, which can be located to alarm inside or outside the room where the motion sensor is located. Another option is that the motion sensor sends a wireless signal to the caregiver pager allowing the caregiver to be notified wherever they are without disturbing residents. The main drawback of all types of PIR motion detectors is false alarms when the resident is sleeping and moving his/her leg, hand, cover etc. to interrupt the PIR device field in an unintended manner. Figure9 shows an example of PIR motion sensor wirelessly signaling the caregiver pager on detecting resident’s movement.

A major problem with both existing commercial products and academic research is that they have deficiencies that hinder pervasive fall detection. For example, for most existing products, the base station must be installed somewhere indoors and the portable sensor must be attached to the patient or to the location where the patient usually resides. Hence, once the base station receives the signal from the sensor indicating a fall, it can automatically communicate with a preset emergency contact using the phone/pager. However, the maximum distance between the sensor and the base station is always limited.

So, fall detection can only be conducted within a small indoor environment. So, it would be ideal, though more expensive, solution to combine several of the previously discussed motion detection system components for achieving more extended connectivity among monitoring devices in addition to have them collaboratively and accurately send an alarm for the caregiver on the movement of an elderly resident in order to accordingly help that resident and prevent him from falling.

Wireless signaling between PIR motion sensor and the caregiver pager

V. CONCLUSIONS

Increased awareness of the occurrence of falls among the elderly and enrollment of efforts to prevent or diminish such events are highly needed in order to improve the quality of life for elderly people and provide them with convenient fall detection and prevention techniques. Despite the considerable achievements that have been accomplished on the field of providing multiple solutions for elderly fall monitoring, detection, and prevention in the recent years, there are still some clear challenges to overcome. Typically, drawbacks previously stated while surveying various types of research and commercial fall detection and prevention solutions, are considered as open issues that have to be considered for further research. Also, regarding detection of falls using camera-based surveillance and image processing techniques, there still some difficulties to overcome. One of those difficulties is the fact that visual fall detection is inherently prone to high levels of false fall detection as what appears to be a fall might not be a real fall, but a deliberate movement towards the ground. In other words, most of current systems are unable to discriminate between real fall incident and an event when person is lying or sitting down abruptly

Furthermore, the area of behavior determination, which is focused on building a behavioral profile of the aging patient and monitoring deviations appearance from the model, is still widely open for further research work. Behavior determination is heavily based on activity recognition and location tracking that detects a typical behavior, which might be caused by decreased health status, progressing disease, or emergency situation. Another challenge is that despite understanding to a great extent the causes of most falls, there is still no many methods to accurately predict that a fall event is likely to occur.

Generally, all monitoring algorithms and approaches for fall detection and prevention relying on only one data provider (movement-sensor, camera, accelerometer, etc.) have their own limitations and do not ensure 100% reliability. In fact, preventing falls and injuries is difficult because they are complex events caused by a combination of intrinsic impairments and disabilities with or without accompanying environmental conditions. Algorithms for fall detection for several environments and the subject's physical condition were rather troublesome; however, a combination of movement sensors and signal-processing technologies can provide more accurate and precise fall detection and prevention approaches. Data fusion based on multi-sensing technology offers many challenges for providing more accurate approaches for fall detection and prevention. Multi-sensor data fusion is the area focusing on creating multi-modal systems, which receive data from several providers and perform correlation or fusion upon it in order to increase the accuracy and reliability of the proposed systems. Moreover, combining multi-sensing data fusion technology with prediction technologies such as Machine Learning and Artificial Intelligence approaches will support developing intelligent fall prevention system based on fall prediction.

Finally, elderly people in long-term care centres or aging persons with cognitive impairment, who have not widely considered in this survey, are as well at high risk of falling and more specialized technology solutions must be developed specifically for these populations.

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