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Systematic review with meta-analysis of fall detection systems for elderly care: perspectives for an aging population in Japan

Wataru Hoshi
Tabor Academy, United States
wataruhoshi1113@gmail.com

Abstract

A combination of demographic, social and economic factors are causing an immense strain on the elderly care systems of Japan and other countries with aging populations. Advances in automation offer promising means of reducing labor costs while also improving the lives and privacy of those in care. Here, we aim to analyze the feasibility of automatic fall detection systems for the elderly, gain an understanding of the current status of fall detection and its possibilities, and finally, examine the steps necessary to overcome current limitations. Using systematic review methods, papers were searched in PubMed and screened based on inclusion and exclusion criteria. Seven papers were used to create a quantitative synthesis. There was a large variation of fall detection methods that used wearable, ambient or both types of sensors, combined with unique algorithms to interpret whether a fall has occurred. The difficulty in ethically and safely using elderly people as subjects remains an issue in fall detection tests. The lives of our grandparents, parents and eventually ourselves can be saved through the development of this technology.

Introduction

Japan is a prime example of a country facing the issue of an aging population caused by decreasing birth and death rates. According to the Statistics Bureau of Japan (2020), it has quickly surpassed nations such as Germany and Italy in percentage of elderly citizens and has one of the world's highest mean ages. The proportion of people aged 65+ surpassed the child population since 1997 and made-up 28.4 percent of the population in 2019 (Statistics Bureau of Japan, 2020). Not only is the elderly population growing, but so is the demand for care workers. By the end of fiscal 2025, 550,000 additional care workers are predicted to be needed (Yasuo, 2020). Combined with the high stress and low pay of the job, it is not surprising that a shortage of elderly care workers exists as a major problem in the nation.

A variety of new technologies have been developed with a wide range of utility all designed to relieve the strain on the elderly care systems by decreasing the need for labor through automation while also improving the lives of those in care. With the growing advancements in home automation, new monitoring systems strive to keep senior citizens safe in their homes or care facilities without the constant attention of a human caretaker. There are attempts to both integrate technology with existing items, such as beds and walking frames, as well as to create new devices such as braces to assist in movement. Medicine dispensing and routine health checkups are increasingly done by automatic and digital systems. The social interaction and companionship that many care workers provide is often overlooked, but researchers have attempted to automate the inherently complex human factor of elderly care. There are several robots that try to simulate the emotional care that these workers do with varying success including Paro and Pepper (Foster, 2018). That said, automation in elderly care is still far from reaching its full potential and achieving widespread adoption.

As people age, their decline in sensory, physical and cognitive abilities can often lead to falls that can cause serious injury or even death. According to the Center for Disease Control, falls are the most common cause for traumatic brain injuries and are the cause of 95% of hip fractures. Up to three million older people are treated in emergency departments for injuries caused by falling every year (Center for Disease Control). This statistic will continue to rise as the elderly population increases and existing healthcare systems struggle to keep up. Combined with the undermanned status of many care facilities, utilizing some form of logistically and financially viable and effective fall detection system becomes imperative to saving lives. Here, we conduct a systematic review to provide a deeper understanding of the potential and limitations of automated fall detection technologies in elderly care.

There are a few ways fall detection systems have been engineered. One type is the wearable fall detectors which utilize sensors such as accelerometers and gyroscopes by having the user carry or wear it in some form. The combination of increased electronic device ownership (in the form of phones and smart watches) as well as more affordable, smaller and effective sensors mean that the potential for these fall detection systems are rising. However, many of these items such as vests and belts can be intrusive and restrict movement. Because these systems require the user to consistently have them equipped and do so on their own volition, any discomfort is detrimental to its ability to do its job. Another obvious issue is battery life. Since users may be unable to recharge any devices for a multitude of reasons or just simply forget to, the length of battery life must be maximized, and the complexity of charging simplified to reach a point of viability. Ambient systems can overcome some of these issues. By using various sensors such as infrared and pressure mats to observe the movement within a room, algorithms can detect when a fall has likely happened. They do not encumber users and require little to no interaction to work. However, ambient systems have their own flaws. Unlike wearable sensors, the location/area that these systems are effective are limited to closed spaces with as little interference as possible. Observation systems can also be a major source of privacy concern.

By utilizing a systematic review with meta-analysis, we aim to gain an understanding of the design and technology used in fall detection systems, as well as their varying capabilities. Simultaneously, through the categorization of the detection type, we can determine the most effective strategies and technologies for fall detection. Due to the simpler design, we hypothesized that wearable fall detection systems would perform better than ambient ones.

Method

Search Methodology

To collect the papers on this topic, a search engine called PubMed was utilized. PubMed searches the MEDLINE database, which includes references and abstracts in the fields of life sciences and biomedicine. The search terms “elderly care”, “senior care” were used in conjunction with “fall detection” and “fall recognition”. Citations were exported from PubMed and organized using Zotero, a reference management software. Each group of results were scanned separately for relevance using the title; the abstract was used when necessary due to any ambiguities regarding the paper’s research objectives. Duplicates were removed after combining the remaining papers. This search was done between the dates of August 2nd and 19th, 2021.

Inclusion and Exclusion criteria
Only papers published in English were included. Papers that included tests of fall detection systems were selected. From these, papers that reported one or more of accuracy, sensitivity, or specificity as outcomes were used. Since the focus of this study is on automatic fall detection, papers on fall prevention and prediction systems were excluded. In order to have a standard form of measurement for the effectiveness of the various fall detection systems, accuracy, sensitivity and specificity were chosen. It is relevant to note that many papers included some but not all three of these measurements.

Data extract and analysis
Data such as the number of participants, accuracy, sensitivity, and specificity were organized into a spreadsheet. The data from a paper were divided into subcategories when appropriate, such as when different types of a detection system was used.
We initially planned to use the Downs and Black (1998) quality assessment checklist; however, many of the questions did not fit the type of trials conducted in the papers used. Instead, in order to weigh in the quality of the data, the papers were assessed (a scale of 0-5) on how representative the participants in the trials were compared to actual senior citizens that would be using these interventions. This was based on a Downs and Black (1998) quality assessment checklist question "Were those subjects who were prepared to participate representative of the entire population from which they were recruited?". Papers that used subjects closest to the elderly population (60~ years old) were given a 5 while papers that did not use any real people were given a 0.
The weight of a paper's data was calculated by multiplying the number of participants with the quality assessment score. The accuracy, sensitivity and specificity percentages of each paper was multiplied by this weight. The results of this were added together and divided by the sum of all weight values to get the weighted average.

Definition of Accuracy, Sensitivity and Specificity:

Accuracy= (true positive+true negative)/
(true positive+false positive+true negative+false negative)

Sensitivity=true positive/
(true positive+false negative)

Specificity=true negative/
(true negative+false positive)

Results
Through the initial search, 190 papers were found, 64 of which passed the screening for relevance to the topic. Out of these papers, 7 were removed as duplicates. Afterwards, 45 of the 57 were excluded because they did not include data from trials/tests. Of the 12 left, 4 did not use the measurements of either accuracy, sensitivity or specificity and were excluded as well. Of the remaining papers, 1 did not use real people for trials and was excluded from the quantitative synthesis. The final number of papers used for meta-analysis was 7.

The average number of participants was 18.1 people; the greatest number of participants was 50 and the lowest was 0. The paper with 0 participants relied on computer-simulated falls to measure accuracy, sensitivity, and specificity of a virtual ambient fall detection system. The years the papers were published ranged from 2008 to 2020. The average year of publication was 2014.

TABLE 1: Qualitative Summary of Papers Included in Meta-Analysis

Author and year	Type of intervention	Number of participants	Quality assessment (0-5)	Summary of outcomes Accuracy, Sensitivity, Specificity
System Design for Emergency Alert Triggered by Falls Using Convolutional Neural Networks (2020)	Ambient fall detection system that utilizes low-resolution infrared sensors. Tested with 3 types of recurrent neural networks (LTSM, GRU, Bi-LTSM).	4	3	LTSM: 91, 89, 93 GRU: 87.5 85, 89 Bi-LSTM: 93, 93, 93
SisFall: A Fall and Movement Dataset (2017)	A wearable self-developed belt device that utilizes an accelerometer to detect falls.	38	3	Young: 92.684, 95.74, 89.624 Elderly: 88.112, 79.446, 96.76
Validity of a Smartphone-Based Fall Detection Application on Different Phones Worn on a Belt or in a Trouser Pocket (2015)	Smartphone based fall detection that uses built-in accelerometer. Algorithm to generate fall alarm from data. Samsung S3 and S3 mini were worn in belt or trouser pocket.	8	2	Phone on Belt 3: N/A, 75, 97 Phone on Belt 3 mini: N/A, 90, 99 Phone in Pocket 3: N/A, 90, 87 Phone in Pocket 3 mini: N/A, 88, 91
Simulated Unobtrusive Falls Detection With Multiple Persons (2012)	Simulated ambient fall detection system based around the capabilities of a dual-technology sensor (DTS).	0	0	Two Motion Detectors: 93.33, 100, 85.71 One Motion Detector: 66.67, 50, 87.71
TESTING OF A LONG-TERM FALL DETECTION SYSTEM INCORPORATED INTO A CUSTOM VEST FOR THE ELDERLY. (2008)	A tri-axle accelerometer, microprocessor, battery, micro-SD card and Bluetooth module incorporated into a wearable vest.	10	4	N/A
Self-Adaptive Fall-Detection Apparatus Embedded in Glasses (2012)	Glasses with integrated apparatus that uses a tri-axial magnetometer, accelerometer and gyroscope to detect falls.	50	2	System Without Adaption: 90.7, 79.8, 97.7 System With Adaption: 92.1, 81.7 98.7
GAL @ Home (2012)	A fall detection system that combines an on-person tri-axial accelerometer and an optical Imagine Source sensor.	7	2	N/A, 91.35, 95.00
An Energy-Efficient Fall Detection Method Based on FD-DNN for Elderly People (2020)	Wearable fall detection system that uses a tri-axial accelerometer and gyroscope with a focus on low power.	38	4	FD-DDN: 99.17, 94.09, 99.94 LSTM: 96.88, 81.47, 99.57 CNN: 98.13, 87.5, 99.88
Evaluation under real-life conditions of a stand-alone fall detector for the elderly subjects (2011)	The Vigi'Fall has the user attach a micro-sensor at thorax level which works in conjunction with peripheral inferred sensors.	8	5	N/A, 62.5, 99.5

Table 1 provides a qualitative summary of the seven papers included in the meta-analysis.

Sucerquia, López and Vargas-Bonilla (2017) tested a fall detection system based around an accelerometer that is worn on a belt. A gyroscope was included in the design but was not used in the data that was collected. This study was conducted with 38 people (15 elderly). The elderly people in this study only performed physically undemanding and non-fall events except for a singular Judo expert. This person and the group of young adults performed both the ADL (activities of daily living) and falls. The algorithm was trained with (93% accuracy, 96% sensitivity, 90% specificity) and without data from elderly people (88% accuracy, 79% sensitivity, 97% specificity). To take advantage of the growing use of smartphones and their capabilities, Vermeulen et al. (2015) tested a smartphone-based fall detection system that utilizes the built-in accelerometers and processing power. As pointed out by the author, a smartphone device removes the need to buy new equipment while also reducing the stigma of using the device by using something already familiar. The trials specifically used the Samsung S3 and S3 mini on a belt and inside a pocket. Eight healthy adults were used in this study and accuracy was not measured. The test with the phone on the belt had a sensitivity of 75% and specificity of 97% with 90% and 99% for the Samsung S3 mini. For the tests with the phone in a pocket, sensitivity was 90% and specificity of 87%. The mini had 88% sensitivity and 91% specificity.

Gietzelt et al. (2012) combines a wearable tri-axial accelerometer with an ambient optical sensor. To make the tests more realistic for the vision sensors, “different illumination conditions were integrated in the test scenarios”. The tested sensitivity was 91.35% and the specificity was 95%. Only the pre-study results were used for the quantitative synthesis. However, it is noteworthy to mention that when this system was tested outside of a laboratory environment, the vision sensor faced issues due to its limited view. The optimal location to place it was difficult to find and the falls took place outside of the view of the camera or were undetected due to poor lighting.

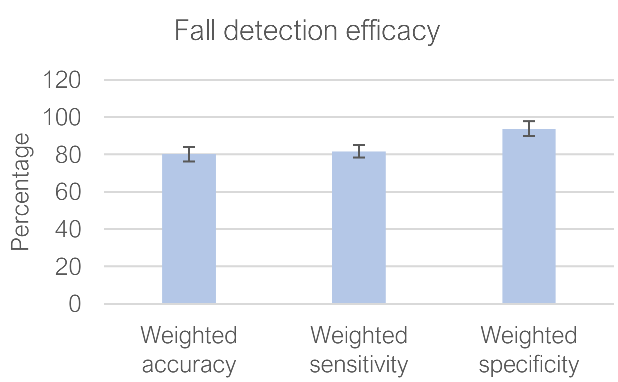

FIGURE 2: Fall detection efficacy.

Figure 2 shows the outcome of the meta-analysis. The final weighted accuracy, sensitivity and specificity were 83.34, 82.44 and 93.6 percent, respectively. Most trial results ranged from 80~99% aside from two outliers well below the mean. Specifically, Bloch et al. (2011) had a 62.5% sensitivity while Ariani et al. (2012) had a 50% sensitivity. There were no clear trends between the characteristics of each paper, such as publication date and the type of intervention, and values for percent accuracy, specificity, and sensitivity.

Discussion

Although the final weighted accuracy values are high, it is important to keep in mind that performance expectations must be high given the repercussions of a faulty reading. The data from the quantitative synthesis conducted suggest that there are capable fall detection systems but require further and more thorough testing before any efforts to properly implement them.

Despite initial assumptions, there was not a positive relationship between how recent the paper was published and the effectiveness of the fall detection system. However, given the lack of standardized trial methods and different types of intervention, there is not necessarily a stagnation in fall detection technology. Similarly, there is no correlation between the number of participants and the years of publication, suggesting a lack of large-scale increase or decrease in efforts to test fall detection systems.

Additionally, there was no correlation observed between the type of intervention (specifically wearable compared to ambient) and effectiveness. My initial assumption was that ambient fall detection systems would perform worse due its more complicated design, but this hypothesis was not supported by our findings.

There are a few things that suggest that these fall detection systems would have performance issues when used in an actual non-trial environment. Many devices had reliability issues ranging from sensor malfunctions to battery death during testing that are not manifested in the data collected. For example, Gietzelt et al. (2012) conducted a follow up experiment to a prenup study where they had 3 elderly patients equipped with fall detection systems for a period of time (separate to the data included in the quantitative synthesis). Two falls out of nine that occurred during this investigation were correctly detected. This is significantly worse than the results from the pre-study that utilized the same system and suggests that the percentages of many of these studies conducted may be deceiving.

Due to the difficult nature of simulating a real fall of an elderly person while ensuring people's safety, many of the papers had to emulate them with fake falls from younger people to collect data. Depending on how this issue was resolved, differing amounts of inaccuracy will exist in the measurements of fall detection system effectiveness. In our study, we attempted to mitigate the differences by incorporating the quality assessment into the weight average calculation. However, the scarcity of actual elderly subjects may nevertheless cause inaccuracies in the results. Older people fall differently than younger, healthier, and more physically stable people.

While we hope that this systematic review provides a fuller understanding of fall detection systems in elderly care, there are a number of limitations to our findings. Differences in methodology and environment of the trials conducted were not accounted for in this analysis. Some of the data may be more accurate than others due to a higher quality of trial methods. The grading of quality using the question "Were those subjects who were prepared to participate representative of the entire population from which they were recruited?" with a scale from 0-5 is somewhat subjective and based on the judgment of a singular person. The search was unfortunately limited to only PUBMED because other electronic databases were unavailable or inaccessible. This limited the number of relevant papers and possibly excluded valuable data that may have given a better idea of fall detection efficacy.

Conclusion

With recent advancements in fields such as sensor technology and artificial intelligence, the potential for fall detection systems are ever-growing. The systematic review showed that several successful methods for fall detection have been developed. However, several steps are necessary for fall detection systems to reach this full potential and achieve widespread adoption. More emphasis must be placed on conducting studies with higher numbers of real elderly subjects in realistic environments to properly understand their capabilities and limitations. Furthermore, many these will likely require varying degrees of improvement in reliability, affordability and comfort before they are practical and realistic for any large-scale distribution. Countries such as Japan that are already facing overburdened elderly care systems caused by an aging population should increase their research and investment into developing and distributing an effective fall detection system.

References

Ariani, A., Redmond, S. J., Chang, D., & Lovell, N. H. (2012). Simulated unobtrusive falls detection with multiple persons. IEEE Transactions on Bio-Medical Engineering, 59(11), 3185–3196. https://doi.org/10.1109/TBME.2012.2209645

Bloch, F., Gautier, V., Noury, N., Lundy, J.-E., Poujaud, J., Claessens, Y.-E., & Rigaud, A.-S. (2011). Evaluation under real-life conditions of a stand-alone fall detector for the elderly subjects. Annals of physical and rehabilitation medicine, 54(6), 391–398. https://doi.org/10.1016/j.rehab.2011.07.962

Bourke, A. K., van de Ven, P. W. J., Chaya, A. E., OLaighin, G. M., & Nelson, J. (2008). Testing of a long-term fall detection system incorporated into a custom vest for the elderly. Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference, 2008, 2844–2847. https://doi.org/10.1109/IEMBS.2008.4649795

Centers for Disease Control and Prevention. "Important Facts about Falls" ://www.cdc.gov/homeandrecreationalsafety/falls/adultfalls.html

Chen, O. T.-C., & Kuo, C.-J. (2014). Self-adaptive fall-detection apparatus embedded in glasses. Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference, 2014, 4623–4626. https://doi.org/10.1109/EMBC.2014.6944654

Gietzelt, M., Spehr, J., Ehmen, Y., Wegel, S., Feldwieser, F., Meis, M., Marschollek, M., Wolf, K.-H., Steinhagen-Thiessen, E., & Gövercin, M. (2012). GAL@Home: A feasibility study of sensor-based in-home fall detection. Zeitschrift Fur Gerontologie Und Geriatrie, 45(8), 716–721. https://doi.org/10.1007/s00391-012-0400-9

Liu, L., Hou, Y., He, J., Lungu, J., & Dong, R. (2020). An Energy-Efficient Fall Detection Method Based on FD-DNN for Elderly People. Sensors (Basel, Switzerland), 20(15). https://doi.org/10.3390/s20154192

Malcolm Foster. (2018).“Aging Japan: Robots may have role in future of elder care” https://www.reuters.com/article/us-japan-ageing-robots-widerimage/aging-japan-robots-may-have-role-in-future-of-elder-care-idUSKBN1H33AB

Sucerquia, A., López, J. D., & Vargas-Bonilla, J. F. (2017). SisFall: A Fall and Movement Dataset. Sensors (Basel, Switzerland), 17(1). https://doi.org/10.3390/s17010198

Statistical Bureau of Japan. (2020). “Chapter 2: Population”. https://www.stat.go.jp/english/data/handbook/c0117.html

Taramasco, C., Lazo, Y., Rodenas, T., Fuentes, P., Martínez, F., & Demongeot, J. (2020). System Design for Emergency Alert Triggered by Falls Using Convolutional Neural Networks. Journal of Medical Systems, 44(2), 50. https://doi.org/10.1007/s10916-019-1484-1

Vermeulen, J., Willard, S., Aguiar, B., & De Witte, L. P. (2015). Validity of a Smartphone Based Fall Detection Application on Different Phones Worn on a Belt or in a Trouser Pocket. Assistive Technology : The Official Journal of RESNA, 27(1), 18–23. https://doi.org/10.1080/10400435.2014.949015

Yasuhiro, Y. (2020, February 5). The Challenges Facing Japan’s Long-Term Care Services. Nippon.com. https://www.nippon.com/en/in-depth/d00530/the-challenges-facing-japan%E2%80%99s-long-term-care-services.html