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Multiple comparator classifier framework for accelerometer-based fall detection and diagnostic

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ABSTRACT

There are a significant number of high fall risk individuals who are susceptible to falling and sustaining severe injuries. An automatic fall detection and diagnostic system is critical for ensuring a quick response with effective medical aid based on relative information provided by the fall detection system. This article presents and evaluates an accelerometer-based multiple classifier fall detection and diagnostic system implemented on a single wearable Shimmer device for remote health monitoring. Various classifiers have been utilised within literature, however there is very little current work in combining classifiers to improve fall detection and diagnostic performance within accelerometer-based devices. The presented fall detection system utilises multiple classifiers with differing properties to significantly improve fall detection and diagnostic performance over any single classifier and majority voting system. Additionally, the presented multiple classifier system utilises comparator functions to ensure fall event consistency, where inconsistent events are outsourced to a supervisor classification function and discrimination power is considered where events with high discrimination power are evaluated to further improve the system response. The system demonstrated significant performance advantages in comparison to other classification methods, where the proposed system obtained over 99% metrics for fall detection recall, precision, accuracy and *F*-value responses.

1. Introduction

Various studies indicate elderly individuals pose a significant risk to falling, where approximately 33% of individuals over 65 years in independent home living [1,2] and 63% of residential care individuals [3] are expected to fall every year. These elderly individuals obtain significant physical injuries from falling including broken bones, internal tissue damage and head trauma. Furthermore, these sustained injuries have been indicated as a leading cause of death among elderly individuals [4]. The risks associated with falling among the elderly population are further high-lighted in importance with the world's significantly increasing ageing population [5]. Additionally, falls are important with respect to other groups of individuals, for example, those with medical conditions, including neurodegenerative disorders such as epilepsy and Parkinsons disease [6], stroke sufferers [7], women during pregnancy terms [8] and workplace related injuries [9]. Where individuals with epilepsy are highly susceptible to falling and obtaining severe brain damage during epileptic seizures [10], 73% of pregnant women require medical treatment from fall occurrence [11] where foetal deaths can occur from sustained injuries [12] and workplace falls are a leading cause of work related injury and of significant related costs [13]. Furthermore, fall occurrences frequently inflict posttraumatic stress on the individual [14,15], where adults over the age of 65 years suffer significantly more psychological stress and depression leading to a lower quality of life where individuals are apprehensive at the risk of falling during common daily tasks [16]. Falls are reported to cost the UK national health service (NHS) £ 1.7 billion every year [17], where patient falls are a significant occurrence within NHS hospitals accounting for 335,171 (20%) of all patient safety incidents in 2014 [18]. Patient associated costs with length of stay in hospitals are significant, where remote sensing technology allows patients to be monitored at home, offering significant cost savings [19], however patients are high fall-risk individuals and could obtain severe additional injuries during fall occurrence [18].

High fall-risk individuals, including the elderly and individuals with medical conditions, may live alone, fall unconscious or are simply unable to raise the alarm and call for help due to injuries sustained during a fall. A fall detection system determines if an individual has fallen, additionally, the fall could be diagnosed to ascertain significant information such as fall strength and direction, which would be advantageous during medical treatment [20]. For example, physicians knowing which direction an unconscious individual fell and received trauma before they have been examined would be highly beneficial towards providing effective and efficient treatment. Furthermore, an automatic fall detection system could significantly reduce fall associated psychological stress and severity of head-trauma during epileptic seizures as any fall would prompt an alarm for a quick medical response appropriate for the occurred fall and obtained fall diagnostic information. Fall detection systems with high fall-risk independent living individuals have been reported to obtain significant improvements for hospitalisation and death with 26% and 80% respective reductions through applying quick and efficient medical aid on fall occurrence detection [21].

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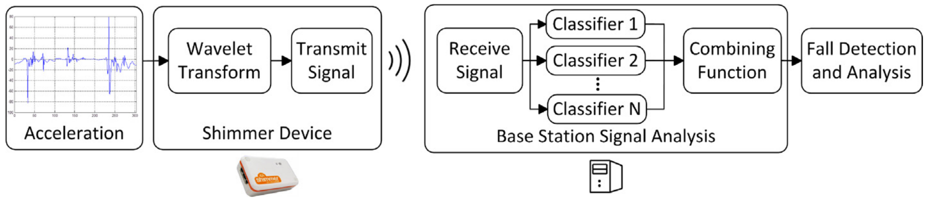

Fig. 1. Conceptual diagram of proposed fall detection system.

Fall detection systems can be grouped into three main categories; visual cameras, environmental sensors and wearable accelerometer-based approaches [22–25]. Visual-based fall detection methods require multiple cameras installed throughout a monitored location, where the various camera captured video-streams are processed to determine if a fall has occurred. Various environmental sensors such as unobtrusive passive vibration sensors can be utilised to obtain fall monitoring systems. Wearable accelerometer devices traditionally determine fall occurrence through thresholding an acceleration signal parameter such as wavelet acceleration sum-vector [26] against an arbitrary value. The arbitrary threshold value within literature is frequently obtained from preknown obtained fall signal analysis [27], where accuracy and false positives are significant issues within implementation [28]. The low-accuracy associated with threshold-based systems have led to machine learning classifiers utilised within fall detection, where classifiers frequently demonstrate significant improvements in comparison to threshold-based systems [26]. Visual-based fall detection systems frequently utilise combinations of multiple classifiers within literature to achieve a performance improvement greater than any single classifier, demonstrating high-performance fall detection [29–31]. Accelerometer-based fall detection systems in comparison have very little recent work undertaken in combining multiple classifier systems to improve performance [32]. Where frequently within literature various classifiers are applied and benchmarked to obtain the classifier best suited to the authors fall database [33–35]. The limited work on multiple classifier systems within acceleration-based fall detection includes: A classifier ensemble proposed for improving fall detection within training limited databases, obtaining 48% correctly classified samples from 45 training data [36]. An activities of daily life (ADL) and fall occurrence discrimination system utilising multilayer perceptrons and radial basis functions, where fall occurrence is determined by a majority voting machine [32]. Similarly, ADL accelerometer-based recognition systems have recently been presented utilising an ensemble of classifiers evaluated with a majority vote [37]. *k*-Nearest neighbours and back propagation neural networks have both been utilised with singular value decomposition to enhance features, demonstrating recognition rates of 95% and 98% for activity recognition, including fall occurrences [38]. These multiple classifier accelerometer-based fall detection systems are limited where implementations frequently are not designed to diagnose fall occurrence characteristics or the classifiers are not being effectively combined to significantly improve the systems overall performance.

The contributions of the work presented in this paper describes a multiple classifier comparator fall detection and diagnostic system for significantly improving fall diagnostic performance. Literature indicates classifiers obtain greater performance than thresholding-based techniques within accelerometer-based fall detection [26]. Various classifiers were recently applied for empirical performance and sensor placement evaluation, where the best performing classifier and sensor location are presented [39,33]. However, there is very little current work within literature for combining various classifiers applied in accelerometer-based fall detection systems to improve system performance over any single classifier implemented [32]. The work presented implements and combines multiple different classifiers with different characteristics to obtain an accelerometer-based fall specific framework on a Shimmer device which significantly improves fall diagnostic performance over any single classifier used, while simultaneously increasing system complexity through combining classifier properties. The fall system utilises artificial neural networks (ANN), *k*-nearest neighbours (KNN), radial basis function (RBF), probabilistic principal component analysis (PPCA) and linear discriminant analysis (LDA) classification techniques [40,41], where the multiple layered neural networks, density distribution and nonparametric density estimation functions characteristics are combined to obtain a performance improvement over any single classifier function utilised. Furthermore, the presented system determines important fall characteristics, including strength and direction, where literature reviews demonstrate few other current accelerometer-based fall systems evaluate fall characteristics [23–25].

The structure of the article is as follows: the significance of fall monitoring with automatic fall diagnostic systems have been discussed. Additionally, techniques for single and multiple classifier systems in fall detection literature have been discussed along with the introduction of the proposed system concept for combining multiple classifiers to obtain an improved performance in fall diagnostics in Section 1. Section 2 describes the Shimmer device and sensing environment for the proposed fall detection system, Section 3 presents the experimental set-up and data collection, Section 4 describes the classifiers utilised in the multiple classifier fall diagnostic system described in Section 5. Section 6 presents the experimental results, while Section 7 discusses the presented comparator classifier fall detection and diagnostic system and the system's performance.

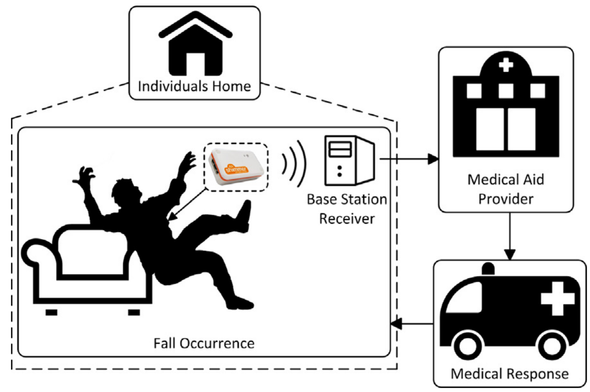

Fig. 2. Sensing environment with fall detection system.

2. Shimmer device system and sensing environment

The proposed accelerometer-based fall detection system utilising a Shimmer embedded device with the presented multiple comparator classifier framework is presented in Fig. 1. The proposed system captures tri-axial acceleration signals with a lightweight, low-power, accelerometer-based wearable Shimmer embedded device [42]. The Shimmer device utilises various physiological sensors in addition to various features including robust design, connectivity, processing and storage capabilities [43], resulting in its high-suitability for the proposed wearable fall detection and diagnostic system. A wavelet transform is applied to the acceleration signal on the Shimmer device to obtain a wavelet acceleration signal, which is then transmitted to a base station receiver for signal processing and fall analysis with various classifiers. The presented fall detection system utilises previously analysed fall and ADL signals to obtain classifiers for determining fall occurrence, strength and direction. The initial classifier results are evaluated with every fall parameter classifier response to obtain a significantly improved fall signal classification response over any single classifier utilised within the proposed system.

The Shimmer device is a small, lightweight, power efficient and flexible sensing platform, capable of real-time data streaming and suitable for wearable physiological monitoring [44] amongst various applications, including telehealth, ambient intelligent health monitoring and mobile health [42]. The Shimmer platform provides computational, communication, storage and optional expandable physiological sensors, e.g. ECG electrodes, as standard. The standard Shimmer platform utilises a MSP430 microprocessor, Roving Networks RN-42 Bluetooth radio, direct computer-to-Shimmer connectivity and various sensors, including low noise and wide range accelerometer sensors [43]. The MSP430 is an extremely low power processor, consuming 5 mA current during use, while offering significant computational capabilities suitable for wavelet [45] and compressive sensing-based sparse signal functions [46].

The Shimmer device is utilised in the presented fall detection system within a sensing environment such as demonstrated in Fig. 2. Where an individual wearing the Shimmer device around their chest has fallen in their home and within range of a base