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Radar Walking Speed Measurements of Seniors in their Apartments: Technology for Fall Prevention*

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Abstract— **Falls are a significant cause of injury and accidental death among persons over the age of 65. Gait velocity is one of the parameters which have been correlated to the risk of falling. We aim to build a system which monitors gait in seniors and reports any changes to caregivers, who can then perform a clinical assessment and perform corrective and preventative actions to reduce the likelihood of falls. In this paper, we deploy a Doppler radar-based gait measurement system into the apartments of thirteen seniors. In scripted walks, we show the system measures gait velocity with a mean error of 14.5% compared to the time recorded by a clinician. With a calibration factor, the mean error is reduced to 10.5%. The radar is a promising sensing technology for gait velocity in a day-to-day senior living environment.**

I. INTRODUCTION

Each year in the United States, over one third of seniors over the age of 65 suffer a fall. Injuries sustained in these falls are one of the leading causes of accidental death in this population [1, 2], and the rate of deaths caused by falls in this population has risen substantially in recent years [3].

Since several studies have shown that better outcomes are correlated with rapid initiation of medical intervention immediately after a fall [4], the authors and others have explored the use of radar and other technologies for detecting falls and relaying the information to caregivers quickly [5].

In the work presented herein, we demonstrate technology that may be used to prevent falls altogether. Such technology would take the form of an in-home monitoring system that captures gait characteristics on a daily basis and reports changes. Research has identified specific gait characteristics which are correlated with higher risk of a falls in older adult populations [6,7]. Nonetheless, many older adults fail to have their gait assessed regularly.

If gait analysis could occur daily in an automated and unobtrusive fashion in the home, changes in gait could be detected and relayed to caregivers very soon after they develop. Caregivers could follow up with clinical and functional evaluations, correct any new underlying medical causes, and put in place assistive or protective technologies if an increase in fall risk is indeed determined to exist.

To this end, we focus on the use of a pulse-Doppler range control radar (RCR). This device estimates the relative velocities of targets within its detection range by transmitting an electromagnetic wave signal and measuring frequency shifts in the reflected waves. Characterization of gait using this device has been described previously [8].

In that work, the device was used in a laboratory setting with actors and clinicians simulating walks typically seen in seniors. The lab also contained a Vicon system, which uses infrared markers worn by the subjects and a sophisticated system of cameras to precisely measure limb and torso movements during the walk. By comparing radar signals to the output of this system, it was demonstrated that the RCR was capable of estimating mean gait velocity, variability, stride duration, and stride duration variability.

Here we demonstrate the use of the RCR system in a more natural senior living environment with walks performed by members of the target senior population. Research was performed at TigerPlace, an independent living environment specially designed and built through a partnership between the University of Missouri (MU) and Americare Corporation. This unique environment provides top quality long-term care while also supporting research and educational opportunities for researchers at MU.

Walks are scripted, and monitored by a staff performing a fall risk assessment (FRA). Since the walk portion of this FRA measures only the time taken to walk a distance of 10 feet, and since additional sophisticated and intrusive systems such as Vicon cannot be put into multiple senior living apartments, we focus here on walking speed. Although a more complete assessment of gait is desirable, gait speed alone has been associated with increased risk of falls even after adjusting for other confounders and clinical scores of balance and cognition [9].

Also deployed in the senior living apartments and used as a gold standard in a portion of the walks is a Kinect-based gait analysis system described in [10, 11]. This system has different trade-offs in privacy, cost, and gait measurement abilities. Although all sensing systems developed by the authors are implemented in a way to protect the identity and activities of residents, depth and vision cameras are widely recognized as first collecting, then protecting this information. Radar does not collect clearly identifiable

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information on identities or activities, and it is likely to be deployed at a lower cost. It is the goal of this work to begin demonstrating that the radar can collect the same clinically relevant gait information as the vision and depth systems, such that the these advantages can be leveraged.

In this paper, we will compare the walking speeds measured by each of the three systems: RCR, Kinect, and manual stopwatch measurement in the FRA. A key strength of this research lies in the fact that these scripted walks were performed in actual senior living apartments by the residents of these apartments. Further, the RCR is unobtrusive, as evidenced by the fact that it has operated day and night in the apartments.

We leave for future research the measurement of additional gait parameters such as stride length and variability, as well as the evaluation of daily unscripted walks.

II. METHODS

Thirteen residents of TigerPlace participated in the overall study. Subjects consist of five males and eight females, aged 75 to 97. Eleven residents walk independently without a walker, cane, or wheelchair during their walking speed assessment, and two use a walker. Seven participants live alone, and the remaining six were made up of three couples sharing their apartment.

Walks were collected during fall risk assessments conducted by study personnel over a three month period from Nov 2011 through Jan 2012. Each subject provided a maximum of one walk per month. Walks were simultaneously observed through the RCR and Kinect gait systems, all described below. Gait velocity measurements obtained through these three different sources were then compared.

A. *Fall Risk Assessment*

Subjects enrolled in the research agreed to participate in monthly FRAs. These assessments were performed in the subjects' apartments by study staff including a trained clinical staff observer who watched protocol and scored each instrument using its standard rubric. The FRA protocol consists of a series of sequences of standing, reaching, walking, and sitting motions chosen to quantitatively measure both functional performance and fall risk. They included Functional Reach, Timed Up and Go, Berg Balance Scale and others.

In the context of the greater FRA, each subject was asked to walk 10 ft starting and ending in a standing position, then turn and repeat in the opposite direction. These were each recorded as separate walks. Subjects were oriented such that these walks were oriented directly towards and away from the radar units. Distance between the RCR unit and the closest end of each walk varied by apartment from just over three feet to almost fourteen feet. The time of each walk was measured with a stopwatch. This measurement was considered the gold standard gait velocity.

B. *Radar*

The radars used in this study are low-cost commercially available pulse-Doppler range control radars (see, e.g., [12]), housed unobtrusively as shown in Figure 2. The radars have been modified so that their baseband signal outputs can be recorded by an external data acquisition system. The radar works by periodically transmitting a 5.8 GHz pulse. The transmitted and returned signals received within a certain time period, which determines the range of the device, are then mixed and low pass filtered. The transmitted signals are reflected from stationary objects at the same frequency, whereas a frequency difference is introduced when a non-stationary object is in the range. A number of different frequency shifts can be observed in the radar measurements rising from the motion of the various body parts. The dominant (in terms of signal energy) return signal is due to the torso and can be used to estimate walking speed. The baseband radar output is sampled at 960 Hz with a commercially available A/D converter, specifically the DATAQ DI-710 data logger [13]. The measurements are transmitted wirelessly to a computer, where they are recorded into a database for post-processing. This radar has been previously demonstrated to be effective in estimating gait velocity, stride rates and the variability associated with these variables in [8].

According to the Doppler principle, velocity is related to the frequency shift in the measurements as follows: $v = c\Delta f/(2f_c)$, where c is the speed of light, Δf is the frequency shift, and f_c is the radar carrier frequency. In order to estimate the frequency shifts from the radar measurements, a Fourier transform based algorithm is employed. The algorithm is outlined below and further details can be found in [8].

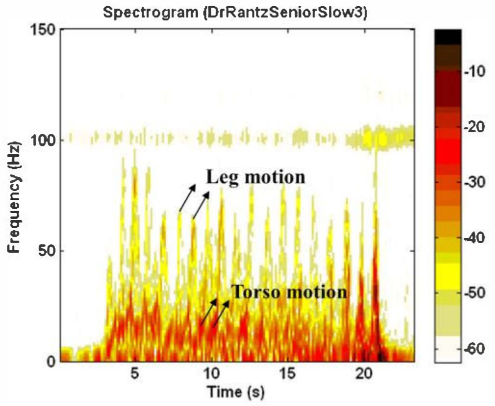

Figure 1 The spectrogram of the radar signal. The unique signatures of the torso and leg motion can be clearly observed. Levels are in dB [8].

For estimating velocity, the raw data is first passed through a band-pass filter with a pass-band region of 5-100 Hz. This removes very low frequency contamination from the data as well as high frequency noise since normal gait velocities correspond to frequencies much lower than 100 Hz (8.5 ft/s). The algorithm then divides the filtered signal into overlapping time segments. The fast Fourier transform (FFT) of each segment is computed after applying a Hanning spectral conditioning window and using an appropriate amount of zero-padding. (Specifically, in this study, we have used segment lengths of 400 time samples, 75% overlap between segments and 4096 point FFTs.) The resulting short-time Fourier transform (STFT) image is smoothed out in the time dimensions with a 3 sample moving average (at every frequency bin). The frequency with the maximum spectral energy at each time instant is then used to estimate the gait velocity. The above process can be repeated iteratively, while adjusting the band-pass filter frequencies adaptively as a function of the estimated gait frequencies in the previous iteration, for improved performance (see [8] for details). Figure 1 shows a sample STFT plot obtained from the radar. As mentioned previously, the dominant returns from the torso can be readily observed. The secondary returns are from the leg and arm motions.

Figure 2 Radar unit in unobtrusive setting (left) Lid removed, showing data acquisition and radar (right)

C. Kinect

As part of the broader research project, subjects agree to have the Kinect-based depth camera fall risk assessment system deployed and operational in their apartments round the clock as shown in Figure 3. This included coverage of times during which FRAs were performed.

Figure 3 Kinect sensor installed in apartment with computer over the refrigerator

As described in previous research [10, 11], this system starts with an image from a Kinect depth camera, performs foreground extraction, and estimates walking speed by calculating the centroid of the foreground 3D point cloud. That centroid is then projected onto the ground plane, and speed is computed from the change in position measured over each frame.

For this research, the Kinect system was used primarily for secondary validation. Both the centroids and images were used to verify the walk data. In addition to absolute gait velocity, the cosine rule was used to translate the centroid's location, velocity, and direction of travel into a measure of subject's velocity relative to the radar. It is this velocity that a Doppler radar actually measures.

As part of algorithms designed to save storage space, the Kinect system only saved data during brief periods where a walk was believed to be present. These algorithms are still in development, and some of the walks--or portions thereof--were not captured for validation by the Kinect system.

III. RESULTS AND DISCUSSION

A. Experiment Scope

From the fall risk assessments conducted from November, 2011 to January, 2012, 16 data sets were available with time-synchronized gait measurements from the FRA, Kinect and radar. In addition 12 data sets were available with time-synchronized measurements from the FRA and radar.

There exists at least one walk from each of 11 different subjects in these measurements. These subjects include 4 men and 7 women, age 75 to 97. Nine of the 11 walked independently during their FRA and 2 used walkers. Seven participants lived alone and the remaining 4 were couples.

B. Comparative Analysis

The FRA velocities are computed by using the time it took for the subjects to walk the pre-designated 10 ft paths, as measured by a stopwatch. Kinect is used to compute the walking velocities as well as the angles during these walks. The eventual goal in this study is to evaluate the gait velocity estimation performance of the radar and compare it with the FRA velocity estimates. Accordingly, in this study, the Kinect sensor will be used to estimate the walking angles with respect to the radar. The radar velocity estimates can then be corrected by using these angle estimates and compared with the FRA (the radar measured velocity is the true velocity of the gait multiplied by the cosine of the angle between the walk orientation and the radar).

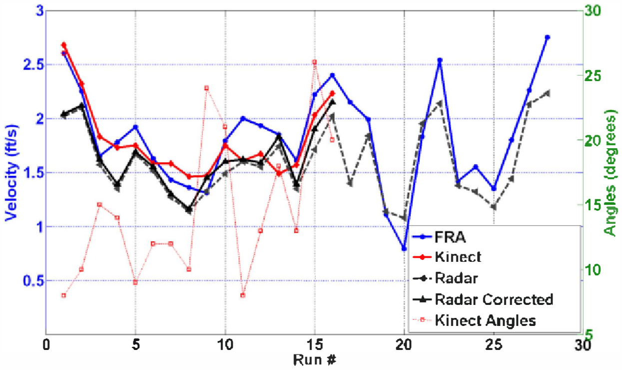

Figure 4 The velocity estimates from FRA, Kinect, Radar and walking angles estimated by Kinect(angles are with respect to the radar).

Figure 4 shows the velocity estimates obtained from the FRA, Kinect and radar measurements for the first 16 runs, and from the FRA and Kinect measurements for the remaining 12 runs. The average walking angles during each walk with respect to the radar and as estimated by Kinect are also superimposed on these plots. It is observed that the radar estimates (both before and after accounting for walking angle) are in very good agreement with the FRA measurements. The radar velocity errors can be computed with respect to the FRA as follows: $|v_{\mathrm{Radar}} - v_{\mathrm{FRA}}|/v_{\mathrm{FRA}}$.

The error levels obtained using this formula are shown in Figure 5. The blue dots in this figure represent the 16 samples for which Kinect walk angles are available. The remaining 12 samples are shown with the circles. The solid line shows the average radar error over all of the 28 runs. The dashed line, on the other hand, is the average of the radar error samples for which the Kinect angles are available. In addition, the errors after angle corrections for these sample points are shown on the right hand side. The average absolute error is 14.5%. The average error decreases to 11.9% when the radar velocities are corrected for angle in the smaller subset for which that angle was available from the Kinect system. Note that the difference is not dramatic because the walk angles are relatively small in most of the runs as observed in Figure 4. During FRA's the walking paths are arranged to be as much towards and away from the radar as possible, hence resulting in small angles.

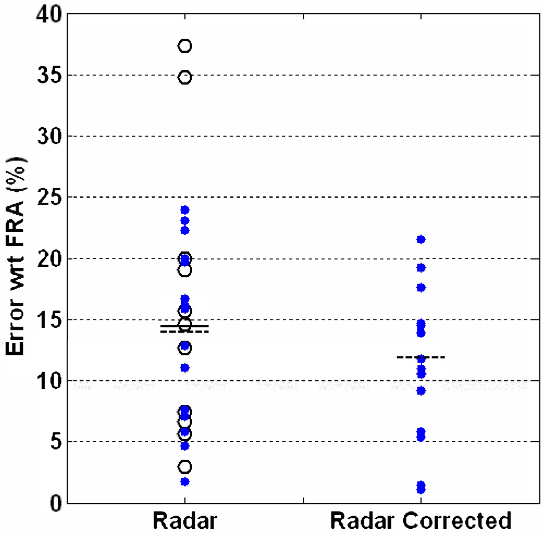

Figure 5 The velocity estimation error of the radar computed with respect to the FRA. The blue dots represent the 16 samples where corrected radar estimates are available and the remaining 12 samples are shown with the black circles. The solid line represents the overall mean of the radar velocity errors and the dashed lines represent the mean of the radar velocity errors for the first 16 samples (the blue dots).

It is important to note that in the broader dataset, the radar is underestimating gait velocity in the vast majority of cases. By adding a calibration factor of 0.19 ft/s to the radar gait velocity, the average error is reduced to 10.5%.

IV. CONCLUSIONS AND FUTURE DIRECTIONS

We have presented a Doppler radar-based gait monitoring system and deployed it to eleven senior apartments. In 28 scripted walks, the system measured gait velocity to within 14.5% of measurements taken by a clinician with a stopwatch. When the precise angle of the walk relative to the radar is known, and corrected for, the accuracy is improved to an average of 11.9%. With a calibration factor, the average error is 10.5%. This is a promising first step in showing the ability of the radar to measure gait velocity in a typical senior living environment.

Measurements were taken using a continuous monitoring system housed in a small unobtrusive piece of furniture, with the system remaining in operation around the clock for several weeks. This further demonstrates the feasibility of collecting daily gait monitoring data in a home environment.

The next important step will be expanding the system to measure unscripted walks throughout the day. This will involve either controlling or measuring the angle of the walk in order to maximize accuracy of the radar. It will also require removing outliers caused by visitors, pets, meandering walks, etc. From the collection of daily walks, a gait characterization score will be obtained. It is this score that can be monitored with trend or anomaly detection algorithms in order to trigger alerts to caregivers. Such a system holds great promise to reduce falls and fall-related injuries in seniors.

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