Quantitative Gait Measurement with Wave Doppler-radar for Elderly Walking Speed Recognition

Maha Reda[1], Aly Chkeir[1], Racha Soubra[1] and Mohamad Nassereddine[2]
[1]University of Technology of Troyes, Troyes, France
[2]Lebanese University, Faculty of Sciences, Hadath, Lebanon

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Abstract: This paper studies the use of a device based on a Doppler sensor in estimating the gait velocity in a non-controlled environment. It provides signals of the instantaneous velocity with an irregular time sampling. A high accuracy motion capture system, Vicon, was employed to provide the reference data for device evaluation. The gait parameters have been validated with a Vicon motion capture system in our lab. A proper algorithm based on the Lomb-Scargle periodogram was proposed to extract features from the radar signals such as the dominant frequency and the number of steps performed. These features were then used to calculate gait parameters such as the gait velocity and the step duration on a 5m walking sequence at a normal pace. The results showed the reliability of the Doppler device in estimating the gait velocity (mean error = 5.1%).

1 INTRODUCTION

The elderly population in most European countries is growing significantly. This high increase emphasizes the need for a strategy to maintain the wellbeing of the elderly and enable them to live in good conditions (Chłoń-Domińczak et al. 2014). Even when in their normal environments, old people are subject to highly stressful events due to the decreasing physical ability and activity and to the high risk of pathologies that in most cases lead to frailty. Frail people are vulnerable to the risk of falling that causes tremendous amounts of mortality and morbidity. Researches have shown that the study of factors contributing to frailty can help in predicting falls and eventually preventing them.

Linda Fried's model presents a description of physical frailty based on five indicators (Fried, 2001). Among these indicators, walking speed was proven to be the one that has the greatest correlation with the frailty index (Theou et al. 2011). Walking speed is easy to calculate and this is usually done in clinical tests by measuring the time taken to travel a certain distance (usually 10 m) at a normal pace. However, in order to assess the risk of falling, a continuous study of the walking speed is needed, especially in the home environments of the elderly where they are walking at their normal pace and going about their daily life activities. For that reason, new technologies are needed that are able to calculate the walking speed on a daily basis.

In the work presented herein, we demonstrate the use of a device based on a commercially available Doppler sensor that calculates the instantaneous value of the walking speed. The device emits an electromagnetic wave and returns a square signal with a frequency equal to the frequency shifts.

The velocity is then calculated using the following equation:

$$\Delta \boldsymbol{v} = \frac{\Delta \boldsymbol{f} \times \boldsymbol{c}}{\boldsymbol{f_0}} \qquad (1)$$

where Δv is the calculated velocity, Δf is the Doppler frequency, c is the speed of light and f_0 the fundamental frequency of the radar.

In a previous study (Jaber et al. 2014). The performance of the device was evaluated with reference to clinical tests over a 3m distance. With preliminary signal processing, it was shown to be a reliable device in calculating both the instantaneous and the mean walking speed.

In this study, the range of the Doppler sensor was adjusted so that motion can be captured up to 10m away. We employed a high-accuracy motion capture camera system, Vicon, for ground truth data, and more advanced signal processing techniques in order to improve the capacity of the device to calculate the

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mean velocity. We considered that the highest contribution to the velocity signal of the radar comes from the pelvis since it has the largest surface area (Yardibi et al. 2011). The mean velocity calculated using the Doppler radar signals is then compared to the mean velocity of the center of mass of the pelvis obtained using Vicon. The main challenge in this study was the irregularity of the signals obtained from the Doppler device, which was resolved using the Lomb-Scargle Periodogram (LS) (Scargle et al. 1982). A proper algorithm was proposed to extract features from the radar signals that would help in calculating the gait velocity.

2 EXPERIMENTAL SETUP

2.1 Doppler

The radar used in our study is a commercially available Doppler sensor (X-Band Doppler Motion Detector MDU 1130, Microwave Solutions LTD., Marlow United Kingdom) with a carrier frequency of 9.9 GHz. The device was placed on a 1m high table and was put in a friendly, decorative box in order to be more acceptable for future experiments in an elderly environment. The radar was connected to an application installed on a Tablet via Bluetooth, in such a way that the recorded values of the velocity are stored in a file and sent directly to the Tablet once acquisition is over.

2.2 Vicon

The commercial 3-D motion analysis system, Vicon system, used in this study consists of eight infrared cameras and motion capture software installed in a computer. During the acquisition, the cameras emit infrared light that is reflected by the retro reflective markers put on the moving subject. The reflected light is then picked up by the cameras and eventually the spatial position of each marker in an x, y, and z coordinate system is obtained. In our study, we used 16 reflective markers that were put on the toes, heels, wrists, fingers, shoulders and pelvis. Out of these markers, we were able to extract the exact instantaneous location of the center of mass of the feet, hands, pelvis and shoulders. We considered that the mean velocity of the center of mass of the pelvis yields approximately the mean gait velocity. This velocity was calculated simply by dividing the distance travelled by the center of mass of the pelvis by the time (over 10 ms intervals).

A synchronization system was built in order to make sure that the radar and Vicon are acquiring the same data for the exact walking sequence of each subject. The system consisted of two infrared sensors barriers that detect the start and the end of the walking sequence. These two sensors are connected simultaneously to the Tablet and the Vicon system.

2.3 Protocol and Data Processing

The aim of this study was to compare the velocities obtained by the Doppler device to those obtained by Vicon. Four persons, all of whom were members of the laboratory, had given their informed consent to participate in the experiments. Each subject conducted five 5m walks towards the device, resulting in 20 walking sequences. The signals obtained from the radar contain the instantaneous velocity of each movement detected in an irregular time sampling. To filter the signals and remove high and low frequencies, we used a Butterworth bandpass filter between 5 and 100 Hz, applied to the signal in the time domain. The frequencies contained in the filtered signal were then obtained using the LS periodogram (Eq. 2) which is known for detecting and characterizing periodic signals in an unevenly sampled data (VanderPlas et al. 2018). A time delay (Eq. 3) was added in order to overcome the problem of the irregularity of the signals.

$$P_x(\omega) = \frac{1}{2}\left(\frac{\left[\sum_j X_j cos\omega(t_j - \tau)\right]^2}{\sum_j cos^2\omega(t_j - \tau)} + \frac{\left[\sum_j X_j sin\omega(t_j - \tau)\right]^2}{\sum_j sin^2\omega(t_j - \tau)}\right) \quad (2)$$

$$\tan(2\omega\tau) = \frac{\sum_j \sin(2\omega t_j)}{\sum_j \cos(2\omega t_j)} \quad (3)$$

The frequency with the highest peak corresponds to the frequency of the steps made during the walk (Fig. 3), i.e. the number of steps performed in one second. By inversing this frequency, we obtained the time taken to complete each step for each of the subjects who participated in the experiments. Furthermore, an FFT was also conducted on the radar signals, with a sampling frequency equal to the length of the signal. The frequency peaks obtained from the FFT corresponded to the number of steps performed by the subject during the whole walking sequence. The velocity was then calculated using this equation:

$$v = \frac{distance\ travelled\ (5m)}{step\ time \times number\ of\ steps} \quad (4)$$

As for Vicon, an FFT was also conducted to obtain the frequency of the velocity signals of each center of gravity and then it was compared to the frequency obtained from the LS periodogram applied to the corresponding radar signals. We considered that the gait velocity corresponds to the mean velocity of the center of the pelvis. This velocity is calculated by taking the average of the mean velocities of the four markers put on the pelvis. The mean error was then calculated using this equation:

$$erreur = \frac{|V_{vicon} - VD|}{V_{vicon}} \quad (5)$$

2.4 Algorithm

The algorithm proposed is described in the following steps:

- Filter the radar velocity signal using a Butterworth bandpass filter between 5 and 100 Hz
- Apply the LS periodogram and extract the frequency with the highest energy peak that corresponds to the number of steps performed per second
- Apply an FFT to extract the number of steps performed during the walk
- Calculate the velocity using Eq. 4.

The LS periodogram used was the one integrated in Matlab, where the algorithm was implemented. Note also that in the FFT performed in the third step, the sampling frequency was equal to the Doppler signal length in order to obtain the number of steps. The algorithm was applied to all 20 walking sequences

3 RESULTS AND DISCUSSION

An example of the signal obtained by the radar is given in **Fig. 1**.

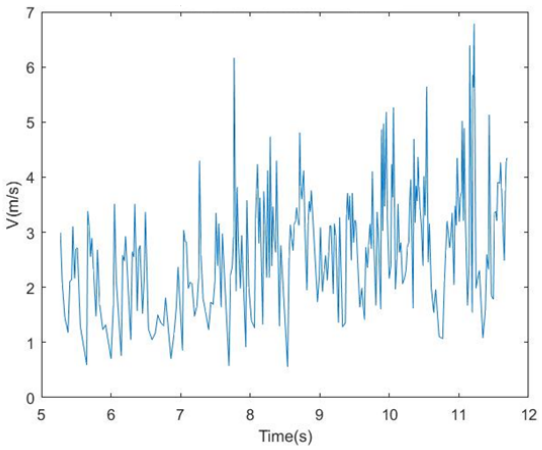

Figure 1: Radar signal.

This signal contains the velocity of each movement detected by the sensor. When applying the filter, we remove the high velocity peaks that correspond to the movement of the limbs and are considered as noise. When comparing it to the Vicon data, we can see that the filtered signal corresponds approximately to the velocity signal of the center of the pelvis (Fig. 2). The frequency content of the Vicon signal is presented in (Fig. 4). The maximum frequency was calculated for all the signals produced by the radar and compared to the corresponding signal obtained from Vicon (Fig.3). We can see that, after filtering, the frequencies of the movement of the limbs are totally removed, and the remaining frequency was that of the pelvis. The number of steps performed during the whole walking sequence is presented in (Fig. 5). By using Eq. 4 we were able to calculate the gait velocity from the radar signals and compare them to the Vicon velocities. Results of

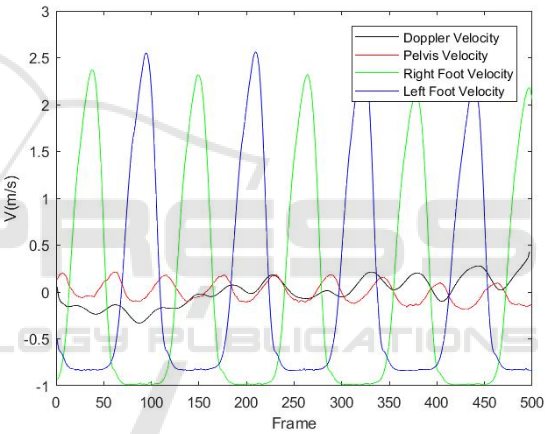

Figure 2: Graphical representation of the velocity signals of the centers of the right, the left feet, the pelvis and the filtered signal obtained from the radar (blue).

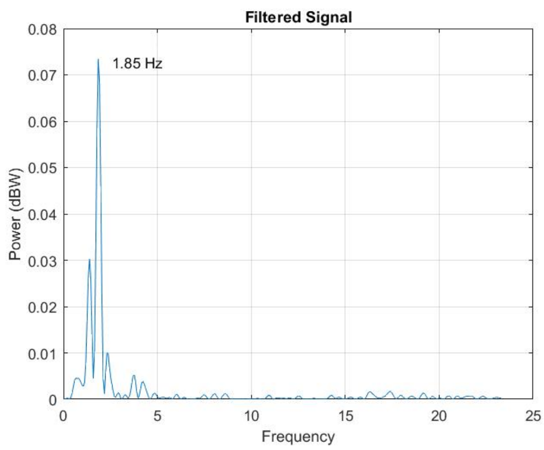

Figure 3: The LS periodogram showing the frequency peaks of a filtered radar signal.

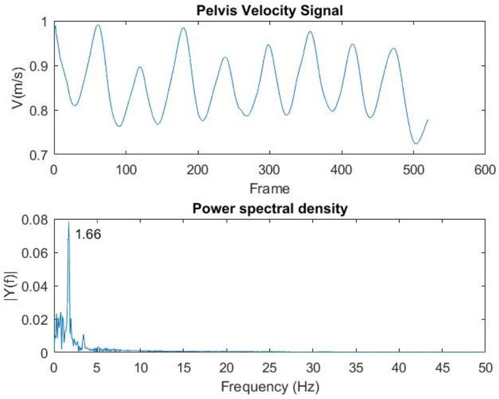

Figure 4: FFT of the pelvis signal obtained from Vicon.

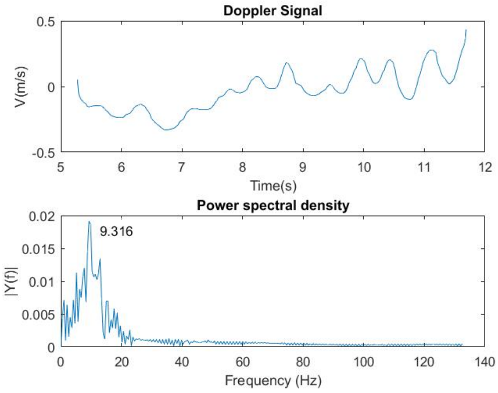

Figure 5: FFT of a radar signal showing the number of steps (9.316 steps).

18 walking sequences were obtained (Fig. 6). Two sequences were found to be corrupted and were not used in the study.

However, the results shown here correspond to a small group of young people (between 23 and 28 years old) and does not represent the results on the elderlies. Another limitation of the study was the necessity to know the distance travelled beforehand in order to perform the algorithm.

The mean error obtained is 5.1%. Compared to previous studies (Cuddihy et al. 2012), where the radar signals had a regular time sampling, in this study we were able to obtain an approximate value of the gait velocity with a lower mean error, even when we were dealing with irregular velocity signals.

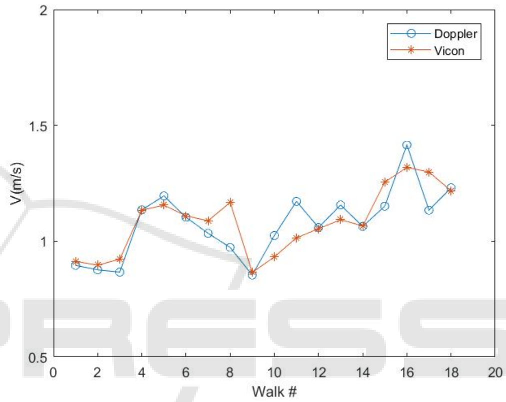

Figure 6: Mean gait velocity estimates obtained from Vicon (red) and the radar (blue).

4 CONCLUSION

In this study, we used a device based on Doppler sensor in order to estimate the gait velocity. The device was designed in a friendly, non-intrusive way in order to be more acceptable to elderly environments. The performance of the radar was evaluated by comparing its values to the values obtained from the Vicon motion capture system. An algorithm based on the LS periodogram was proposed to estimate gait velocity and step duration.

The periodogram has shown its reliability in extracting the frequency content of the Doppler irregular signals without the need to specify an exact sampling frequency The results were compared to the ground truth data of Vicon and demonstrated the reliability of this algorithm in estimating the gait velocity. In future work, more results need to be validated on a larger group consisting of elderlies and a new method should be developed that could calculate relevant gait parameters without previous knowledge of the distance travelled.

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