Feasibility Validation on Healthy Adults of a Novel Active Vibrational Sensing Based Ankle Band for Ankle Flexion Angle Estimation

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Abstract—*Goal:* In this paper, we introduced a novel ankle band with a vibrational sensor that can achieve low-cost ankle flexion angle estimation, which can be potentially used for automated ankle flexion angle estimation in home-based foot drop rehabilitation scenarios. *Methods:* Previous ankle flexion angle estimation methods require either professional knowledge or specific equipment and lab environment, which is not feasible for foot drop patients to achieve accurate measurement by themselves in a home-based scenario. To solve the above problems, a prototype was developed based on the assumption that the echo of a vibration signal on the tibialis anterior had different acoustic impedance distribution. By analyzing the frequency spectrum of the echo, the ankle flexion angle can be estimated. Therefore, a surface transducer was utilized to generate frequency-varying active vibration, and a contact microphone was utilized to capture the echo. A portable analog signal processing hub drove the transducer, and was used for echo signal collection from the microphone. Finally, a Random Forest regression model was applied to estimate the ankle flexion angle based on the spectrum amplitude of the echo. *Results:* Five healthy subjects were recruited in the experiment. The regression estimation error is 4.16 degrees, and the R^2 is 0.81. *Conclusions:* These results demonstrate the feasibility of the proposed ankle band for accurate ankle flexion angle estimation.

Index Terms—Ankle flexion angle estimation, active vibrational sensing, wearable sensor.

Impact Statement—This paper proposed a low cost, wearable, and convenient method for automated ankle flexion angle estimation, which could be used in millions of home-based scenarios for foot drop patients and pave the way for better and ubiquitous rehabilitation.

I. INTRODUCTION

FOOT drop is a common and grievous disease that causes falls and other injures [1]. The leading cause of this disease is peroneal neuropathy at the neck of the fibula, and its rehabilitation requires a tremendous amount of time and effort [2]. The ankle flexion angle is a critical parameter in the foot drop rehabilitation both for the patient's rehabilitation progress evaluation and for the ankle foot orthosis control [3]. Therefore, accurate ankle flexion angle measurement is vital to foot drop rehabilitation and deserves further research. There are many ways to measure the ankle flexion angle. The most traditional method is manually measuring by goniometer (angle ruler), and the accuracy largely depends on the ability of experimenters. Mechanical methods are commonly used in the clinical environment or integrated into the orthosis due to their high accuracy and low cost [4]. The mechanical methods usually utilize a rotating frame, attach the ends of the frame to the foot and shank and measure the intersection angle of the frame to get the ankle flexion angle [5]. However, the instruments are usually cumbersome and will be inconvenient in daily life for continuous measurement. Optical methods are commonly used in ankle flexion angle measurement in laboratory environments and can be generally categorized into two types: marker-based and marker-free. VICON is the representative marker-based method, and it has a high measurement accuracy and an extremely high price [6]. Marker-free methods are usually based on RGB cameras and deep learning algorithms. Compared with VICON, the marker-free methods are much cheaper, but the measurement accuracy is also relatively low [7]. In addition, both of the methods are not portable and can only be used in well-designed and confined laboratory environments.

Recently, wearable-sensor-based methods have drawn lots of attention from both academia and industry [8]. The most

successful wearable solution is the IMU-based ankle flexion angle measurement method [9]. Research has validated that the IMU-based method can achieve the same accuracy as the optical methods [10]. However, measuring ankle flexion angle with IMU needs multiple sensors to form a sensing network (put each IMU on each body segment) and imposes a high requirement on the sensor synchronization. In addition, the IMU placement error and orientation error will also degrade the accuracy [11]. Acoustical sensing is also an effective angle estimation method. The most representative method is ultrasound imaging [12]. Yang *et al.* [13] achieved simultaneous wrist/hand angle estimation using wearable ultrasound sensors. The advantage of the ultrasound method is that it has a higher spatial resolution and estimation accuracy [14], [15]. The disadvantage of the ultrasound method is that the devices are usually bulky and expensive, power-consuming, and require a coupling medium [16]. Active vibrational sensing is also a promising method. Ikeda *et al.* [17] analyzed the influence of different muscle conditions and ankle angles on the vibration echo. Kato *et al.* [18] used active vibrational sensing to estimate hand posture.

To solve these problems, this paper developed an acoustic-based wearable ankle band for ankle flexion angle measurement. Compared with previous methods, the proposed method was wearable, low cost, and easy to use. This method could be used for automated ankle flexion angle estimation of foot drop patients in home-based rehabilitation. It could also be integrated into ankle foot orthosis to provide intuitive and ubiquitous control.

II. METHODS

Based on anatomy knowledge, the ankle's flexion is controlled by the tibialis anterior [19]. Previous research shows that under different morphology, muscles will show different acoustical characteristics [14]. Studies demonstrated that different hand poses would cause different vibration signal propagation patterns on the wrist, and the hand poses could be estimated by analyzing the vibration echo [18]. Ikeda *et al.* [17] also found similar phenomenons on the ankle, that the vibration echo change with the ankle flexion angles. Therefore, we put forward an assumption that the vibration echo on the ankle can accurately estimate the ankle flexion angle.

The proposed an ankle band consisted of a surface transducer (COM-10917, SparkFun, U.S.) to generate sweeping vibration and a contact microphone (CM-01B, TE connectivity, U.K.) to capture its echo (Fig. 1). The transducer was driven by an analog signal processing hub (Analog Discovery 2, Digilent, U.S.), and the signal collected by the contact microphone was also sampled by it. There is other research using active vibrational sensing and similar sensor setup to measure joints angles in other parts of the human body [17], [18], [20]. Therefore, we utilized their characteristics as our initial value. Then conducted groups of pilot experiments to adjust them to fit our using scenario. We tested signal waveforms, including sine wave, square wave, triangular wave, zigzag wave, and white noise. We also tried different signal parameters, including amplitude, period, and frequency's sweeping range. The result showed that the signal would have
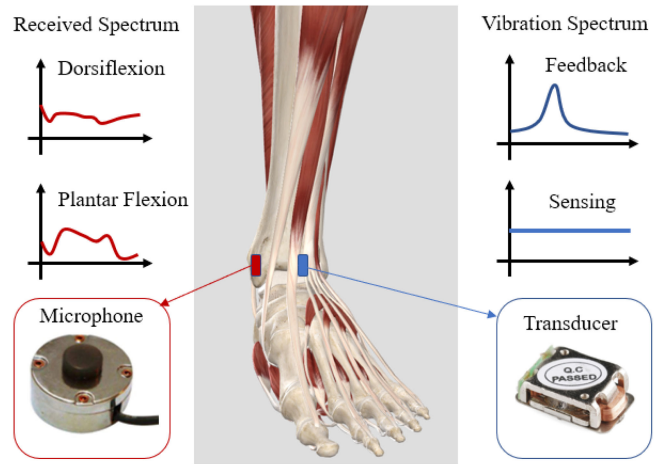

Figure 1. The framework of the acoustical sensing system (the foot model was adopted from the Complete Anatomy, 3D4Medical Ltd). The sensing system contains two parts: a transducer to generate vibration signals and a microphone placed on the skin to collect echos. The system's working principle is that different morphology of muscle will affect acoustic impedance distribution of the vibration signals, and ankle flexion angles can be estimated from the amplitude spectrum of the echos.

better quality with a larger amplitude, but the transducer would generate more heat, making users uncomfortable. The period and sweeping range should be as shorter as possible since it will improve the system's real-time ability. However, if the period is too short, the transducer can not generate enough energy to trans through the muscle. The sweeping range should also cover enough frequency range to carry enough muscle information. According to the pilot experiment results, the final vibration signal we chose was a sine wave, 1 V amplitude, sweeping range from 100 Hz to 1700 Hz with 100 ms period.

Five healthy subjects (four males and one female, yr: 24.2 ± 1.47) were recruited and participated in the experiment. All subjects were fully informed about the experiment's purpose, method, and potential risks and gave consent before the experiment. This research was also approved by Imperial College Research Ethics Committee under the reference of 19IC5680. Each subject wore the ankle band prototype on the ankle. The surface transducer was placed on the tibialis anterior (left foot) to generate the vibration signal. The contact microphone was placed on the tibia bone (left foot) to capture the echo for ankle flexion angle estimation. The portable analog signal processing hub was attached to the subject's leg to serve as a waveform generator and analog-digital converter. An electro-goniometer (SG110, Biometrics, U.K.) was attached to the subject's foot to capture the ground-truth ankle flexing angles (Fig. 2). The electro-goniometer is a wearable goniometer specially design for on-body angle measurement. The sensing principle is based on a strainmeter, and its measurement error is within two degrees.

Under the condition of no load on their legs, the subjects were seated for the experiment and actively controlled the ankle flexion angle during experiments. The natural angle was set as 90 degrees (the shank was perpendicular to the sole of the foot). The ankle flexion angle would decrease when the subject
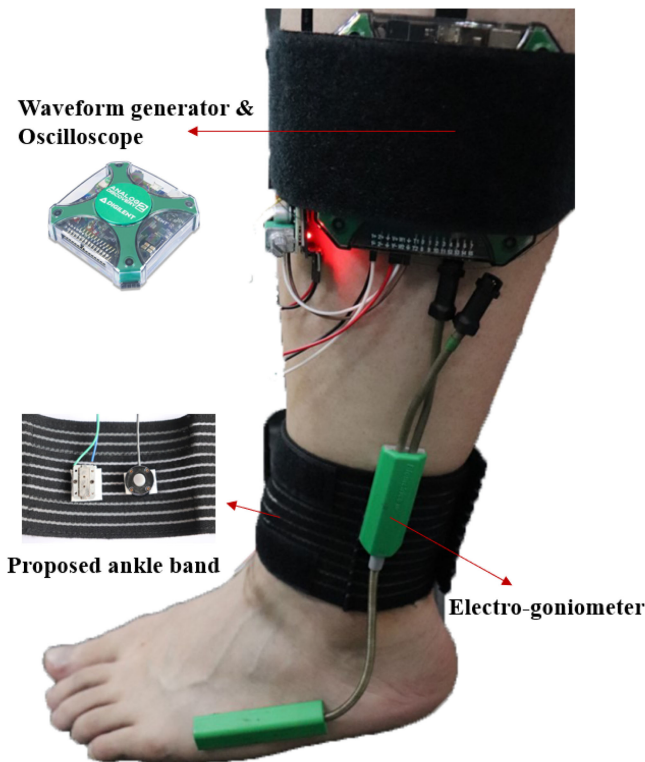
Figure 2. Experimental setup: the ankle band consists of a transducer and a microphone placed on the subject ankle. An analog signal processing hub (Analog Discovery 2, Digilent, U.S.) was tied up on the subject's shank to drive the transducer (COM-10917, SparkFun, U.S.) to generate vibration signals and sample the echos collected by the contact microphone (CM-01B, TE connectivity, U.K.). An electro-goniometer (SG110, Biometrics, U.K.) was attached to the subject's foot to capture the ground-truth ankle flexing angles.

performed dorsiflexion and would increase when the subject performed plantar flexion. Since the minimum angle and the maximum angle of the ankle varied from person to person, each subject was measured separately. To validate the ankle flexion angle estimation accuracy, thirteen different ankle flexion angles from maximal dorsiflexion to maximal plantarflexion angle were evenly selected during the experiments. The angular difference between adjacent poses was around four degrees. Subjects were asked to perform these thirteen angles in sequence for data collection. Each trial of the data collection started at the minimum angle, ended at the maximum angle, and subjects needed to control the ankle flexion angle actively. Each subject had to go through three trials during the experiment. During the experiment, subjects were given a ten-second break to relax before performing each specific angle, and after each trial was finished, the subject was given one minute break to relax.

The sampling frequency of the contact microphone was 5 KHz. The collected raw data were segmented into 200 ms per segment, with a 50% overlap. Each segment consisted of two full sweeping signal periods. After the data were segmented, a high-pass filter was applied to filter out the environmental interference below 100 Hz. Fourier transform was applied to extract the frequency features and then filtered by the Savitzky-Golay filter for noise reduction. In this paper, we used the amplitude spectrum as

the input feature. Therefore, the regression model will output an ankle flexion angle every 200 ms with 1000 input data (feature). A Random Forest algorithm was applied to estimate the ankle flexion angle. The Random Forest algorithm is a machine learning method that can be used for both classification or regression tasks. The benefit of using the Random Forest algorithm is that it can process high dimensional features (e.g., amplitude spectrum).

III. RESULTS

The relationship between the ankle flexion angle and the echo was mainly reflected in the acoustic impedance distribution. When subjects performed a plantar flexion, the tibialis anterior had a higher acoustic impedance to vibrations with a frequency between 1.1 KHz to 1.5 KHz but had a lower acoustic impedance to vibrations with the frequency between 400 Hz to 600 Hz. And when subjects relaxed, the tibialis anterior had a higher acoustic impedance to vibrations above 1.2 KHz but had a lower acoustic impedance to vibrations under 1 KHz. In addition, the acoustic impedance of the tibialis anterior has useful information under 1.8 KHz and will not generate useful information above 2 KHz.

Two evaluation metrics were used to validate the feasibility of the proposed method: estimation error and R^2.

$$Estimation\ Error = \frac{1}{n} \sum_{n}^{i=1} |y_i - \hat{y}_i| \qquad (1)$$

$$R^2 = \frac{SSR}{SST} \qquad (2)$$

$$SSR = \sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2 \qquad (3)$$

$$SST = \sum_{i=1}^{n} (y_i - \bar{y})^2 \qquad (4)$$

where y_i is the true ankle flexion angle measured by the electro-goniometer. $\hat{y}_i$ is the estimated ankle flexion angle generated by the regression model. $\bar{y}$ is the average value of the ankle flexion angle. n is the size of the dataset. SSR is the regression sum of squares and SST is the total sum of squares.

Twenty rounds of Monte Carlo cross-validation used 50% of data to train the participant-dependent models and the rest for validation. The Bland & Altman test [21] was also conducted to validate the consistency of the proposed ankle band with the electro-goniometer (Fig. 3), which is an accepted clinical measurement system [22]. The proposed ankle flexion angle estimation method achieved a high estimation accuracy (Table 1). The unit of min angle, max angle, and error is degree. The average estimation error was 4.16 degrees.

IV. DISCUSSION

This paper proposed a novel ankle flexion angle self-measurement method for foot-drop patients, but the working principle of the method is still controversial. The results demonstrated that the vibration signal's echo had a high correlation with

(a)

(b)

(c)

(d)

(e)
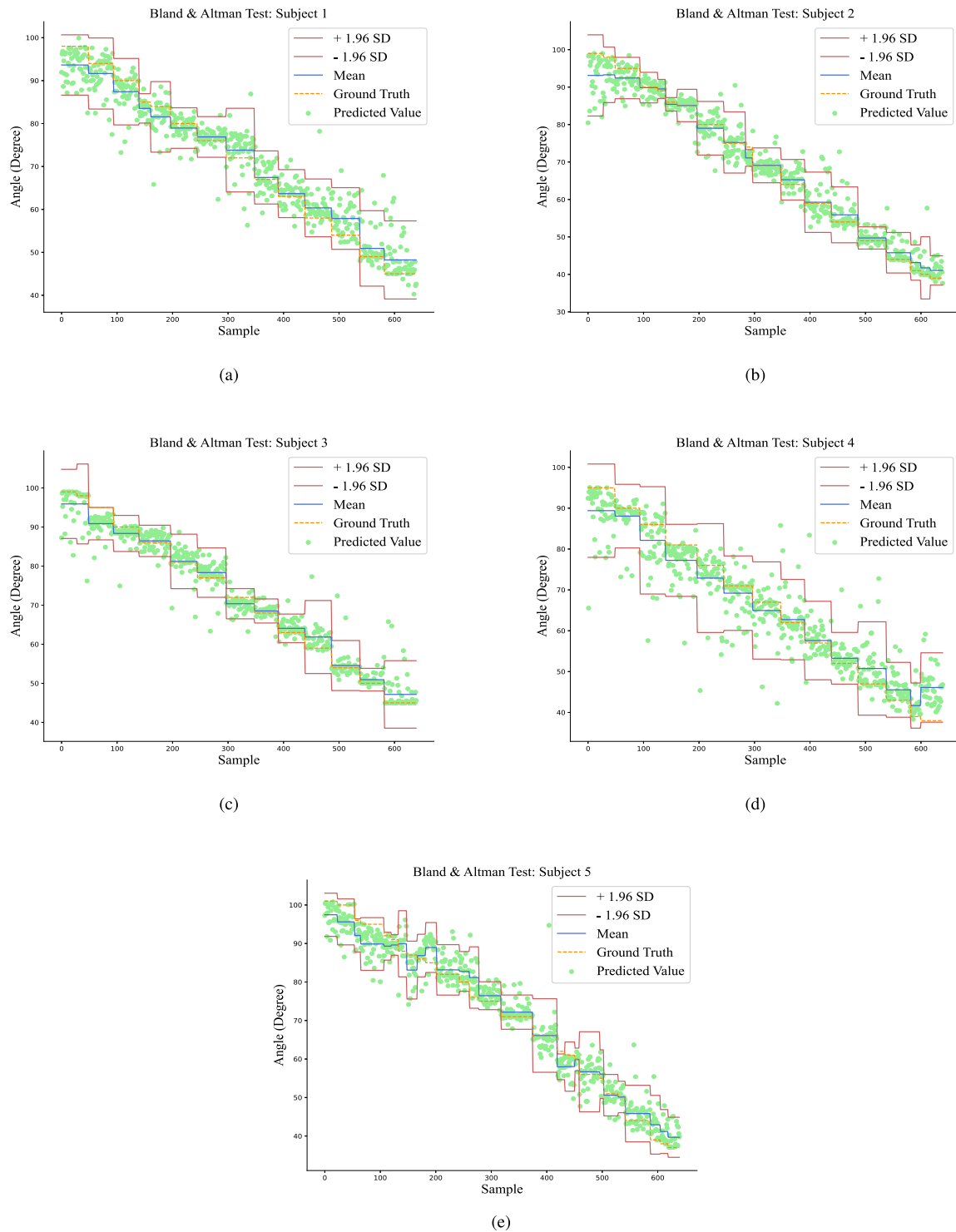
Figure 3. Bland & Altman test on five subjects. Most of the estimation results are within the 95% limits of agreement, which showed that the proposed ankle band could be an alternative method for electro-goniometer.

the ankle flexion angle from the experiment results. However, this phenomenon can be attributed to many factors, including morphological muscle deformation, skeleton deformation, and even the change of contact condition [23]. Some researchers think that the echo is mainly affected by the skeleton and conducted posture recognition on human hands [18]. However, in this experiment, we think morphological muscle deformation

plays a more important role. In this experiment, the transducer and microphone were placed on the same bone, and only muscle deformation happened on the spreading path of the vibration signal. Therefore, we think that the working principle of the proposed method is that the tibialis anterior has different acoustic impedance distribution to different frequencies of vibration signal, and the acoustic impedance distribution is related to

Subject	Min Angle	Max Angle	Error	R^2
1	82	135	3.99	0.833
2	80	141	4.37	0.744
3	81	135	4.87	0.774
4	85	142	3.40	0.821
5	77	141	4.17	0.876
Average	81	139	4.16	0.810

TABLE 2.
METHOD COMPARISON

Methods	VICON	Kinect [7]	IMU [9]	Ours
Error	0	7.5	1.5	4.2
Cost	High	Medium	Medium	Low
Usability	Low	High	Medium	High
Wearability	Low	Low	High	High

the muscle morphology. Since the ankle flexion angle can be reflected in the muscle morphology, the ankle flexion angle can be estimated by analyzing the echo.

Compared with previous works, the proposed method also has its advantage (Table 2). The VICON visual motion capture system is usually considered the gold standard. However, the VICON system is expensive, unportable, and requires calibration and marker placement before use. Kinect is a visual system that contains an integrated RGB-D camera. Compared with the VICON system, the Kinect does not require markers and is much cheaper. However, the estimation accuracy is also low. IMU-based motion capture system is wearable and accurate. A representative product is the Xsens IMU system. Compared with the Xsens system, our method is much cheaper and does not require multiple sensor networks, which is more suitable for low-cost and home-based self-measurement.

Since our system measures the contraction of tibialis anterior, it could also be used to validate the efficiency of the rehabilitation mechanisms: to determine whether the increased ankle dorsiflexion is due to the recovery of tibialis anterior or just driven by toe extensors. In addition, foot drop patients suffer from increased fall risk. To maintain postural balance, it relies on not only the signals from the central nervous system but also on somatosensory inputs [24]. Prior research has validated that the somatosensory information sent to the foot [25], [26] and ankle [27] can improve postural balance control. In addition, haptic feedback can also accelerate the process of rehabilitation [28], [29]. Since our method already includes a transducer that can generate somatosensory inputs and provide haptic feedback, our ankle band could also help the foot drop patients maintain balance and accelerate the rehabilitation process. Further study will be conducted to find an effective somatosensory inputs pattern and the performance in the real world.

However, the proposed ankle flexion angle measurement method is still in the initial stage. Some false positive cases may exist in certain scenarios. For instance, if the individual

simultaneously contracts the tibialis anterior and the triceps surae, the ankle will not move. However, the muscle-tendon junction of the tibialis anterior will displace proximally by a substantial distance, which will be detected by the system and resulted in a larger error. Also, if the individual restricts the ankle angle but changes the muscle contraction force, the deformation of the tibialis anterior and the estimation result will also be different. To solve the problem, we think the decoupling of posture and force is necessary, and future work can be focused on this issue.

In addition, since our system is currently wired, subjects' motion type and space are limited, hindering our test in a continuous walking situation. Therefore, the performance in a real walking situation and the continuous angle measurement is still needed for further research. In addition, the performance difference between patients and healthy groups is unclear since our method is related to muscle morphology. Whether the acoustic characteristic of the muscle after lesion will show the same results still needs further experiments.

V. CONCLUSION

This paper proposes a novel active vibrational sensing based wearable approach for low-cost ankle flexion angle self-estimation for home-based foot drop rehabilitation. Five subjects participated in the experiment, and the results demonstrated the feasibility and accuracy of the proposed active vibration sensing for ankle flexion angle estimation. This work could facilitate the widespread use of in-home and self-management foot drop rehabilitation methods, which may help the rehabilitation and reduce the cost of foot drop patients.

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