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A Feasibility Study for Measuring Accurate Tendon Displacements Using an Audio-based Fourier Analysis of Pulsed-Wave Doppler Ultrasound Signals

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Abstract—**The accuracy of Pulsed-Wave Doppler Ultrasound displacement measurements of a slow moving "tendon-like" string was investigated in this study. This was accomplished by estimating string displacements using an audio-based Fourier analysis of a Pulsed-Wave Doppler signal from a commercial ultrasound scanner. Our feasibility study showed that the proposed technique is much more accurate at estimating the actual string displacement in comparison to the scanner's onboard software. Furthermore, this study also shows that a real-time Doppler data acquisition from an ultrasound scanner is possible for the ultimate purpose of real-time biological tendon displacement monitoring.**

I. INTRODUCTION

Clinical and research based assessment of the level of damage or functional capabilities of a human hand requires an accurate measurement of tendon displacements. This is traditionally obtained by noninvasive estimations using joint rotation angles and moment arms of the fingers [1]. Generally, this technique has limitations because it assumes the tendon is without interconnections, free to move, and constant throughout the rotation of the finger [1]. In actuality, the tendons have interconnections which will alter the actual displacement of a tendon during rotation. Other invasive methods have used X-ray images with surgically placed metal markers [2]. These experiments are mostly research-based and have limited clinical applications. Other studies have used cadaver hand specimens in order to estimate passive tendon excursions [3],[4]. Since passive tendon excursion is smaller than active excursion, it is difficult to determine the actual excursion experienced during different grip configurations using this method [5]. As an alternative to other non-invasive methods, ultrasound scanners have shown remarkable accuracy to assess tendon damage [6],[7] as well as tendon excursion [4],[8]-[11].

Commercially available ultrasound scanners have many built-in imaging and Doppler functions which can reveal information about tissues, organs and flow estimations. In order to determine tendon excursion from ultrasonic grayscale images, tracking algorithms have been previously implemented [8]. These methods use block matching or cross-correlation techniques to scan each image in a cine-loop to detect and track the moving tendon. These processes usually require a lengthy offline analysis with a lower success rate due to resolution and computational issues. However, Pulsed-Wave or Color Doppler functions have shown improved accuracy in determining tendon excursions. These built-in functions of a typical off-the-shelf ultrasound scanner display real-time velocity spectrograms of the moving tendon and can allow for offline velocity-time-integration (VTI) to estimate the excursion. Furthermore, because the tendon's frequency-shifted Doppler signals returning to the scanner are in the audible range, most ultrasound machines allow for real-time audible output of the signal to the on-board speakers. This audible output occurs at approximately the same time as the displayed velocity spectrograms. Unfortunately, most Doppler ultrasound scanners do not allow for raw data access in order to capture this audible signal in real-time. To address this issue, one research group has created acquisition software that uses an A/D converter to transfer the signal from the ultrasound machine to a PC for analysis [11]. However, their reliability study may be plagued with resolution issues from using a lower frequency transducer with the ultrasonic scanner. Other resolution issues in their study may be due to noise from the A/D converter as well as error accumulations from their choice of processing using zero-crossings. Although cost-effective, zero-crossing detectors have significant limitations when dealing with low velocities or a small sample size [12]. Both of these events occur when dealing with real-time tendon data acquisition and processing. Furthermore, the calculated tendon displacement cannot be reliably compared to the actual tendon displacement. This is because the actual tendon displacement is estimated using unreliable methods such as joint rotation angles and moment arms of the finger.

The aim of the present study is to address the need for an improved method to access and process Doppler-shift data from ultrasound scanners. This is accomplished by comparing the tendon displacement measurement accuracy of our proposed audio-based Fourier analysis technique against that of onboard software of a commercial PC-based ultrasound scanner. This is a feasibility study to show the accurate and real-time displacement estimation capability of the proposed processing technique.

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II. MATERIALS AND METHODS

A. Experiment Set-up

As shown in Fig. 1, the experimental setup consists of a moving string and pulley system that mimics biological tendon motion by allowing the string to slide by a known displacement under an off-the-shelf Doppler ultrasound scanner (LogicScan 128 by Telemed). The LogicScan scanner collects the shift frequencies from the moving string with a 12 MHz transducer, which relay the signal to the portable scanner that is connected to a PC (Fig. 2). The transducer is set on top of two ultrasound gel pads with a cut-out standoff wedge (Aquaflex by Cone Instruments). The proper positioning of the transducer is first obtained by moving the string under the LogicScan's Color-Doppler Mode, which highlights the moving areas onscreen. Once the proper position is obtained, the scanner then amplifies, demodulates and digitizes the echo signal. This is done so that the signal can travel to a PC via USB for further onboard processing and displaying purposes. Simultaneously, the scanner's software on the PC will output an audible shift-signal to the PC's soundcard and display the velocity spectrogram. The soundcard is an integrated SigmaTel with a sampling frequency of 44.1 kHz. The audible signal is obtained in real-time, processed and analyzed in Matlab™. This signal represents the spectrum of velocities that are contained in the selected sample volume positioned on top of the string. For the purpose of determining the accuracy of estimating the string displacement, the scanner's onboard processing and the proposed audio-based processing techniques were tested using 20 experimental trials. For each trial, the string was manually pulled by 9.1 cm ± 0.1 cm.

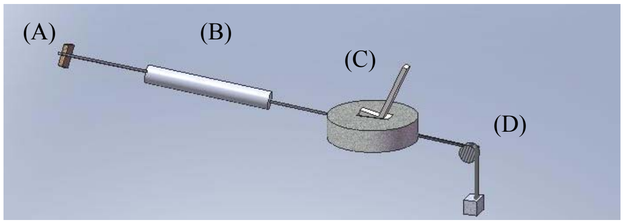

Fig. 1: Schematic diagram of the experimental setup with (A) the string and stopper, (B) string guide, (C) 2 Aquaflex gel pads with cut-out wedge and transducer, and (D) 100 g mass and pulley.

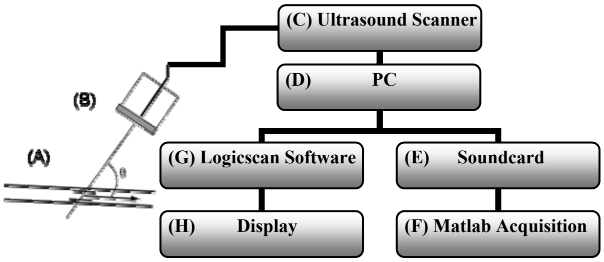

Fig. 2: Schematic of the ultrasound scanner's Doppler signal processing technique: (A) Doppler shifted signal from the moving string [13], (B) 12 MHz transducer, (C) LogicScan scanner which is connected by a USB cable to the PC in (D), (E) the unprocessed Doppler shifted signal is sent to the soundcard where it is collected by Matlab ™ in (F), and, simultaneously, the unprocessed Doppler shifted signal is sent to the scanner's software in (G) for spectral processing and (H) display.

B. LogicScan Scanner's Onboard Software

The string was first located with LogicScan's transducer and several modes were tested to determine optimal settings. The final ultrasound settings of LogicScan are shown in Table 1. The velocity spectrogram is displayed onscreen using LogicScan's software, along with the mean velocity curve. Afterwards, the velocity-time integral is performed using the included tools in order to estimate the displacement of the string. This is compared to the actual string displacement, as well as the estimated displacement that was obtained using our own algorithm.

Pulse Frequency = 2 kHz	Correction Angle = 59°
Gain = 33%	Sample Size = 1 mm
Power Level = 28%	Wall Filter = 7%
Steering Angle = -10°	Dynamic Range = 30dB

Table 1: Selected settings on LogicScan ultrasound scanner.

C. Audio-based Doppler Signal Acquisition and Processing

The Doppler-shifted signal is obtained in real-time from the PC soundcard with a written script in Matlab™. Note that this signal contains noise from previous digitization step in the LogicScan scanner as well as from the soundcard. The noise is reduced by a factor of 10 using a 100-point moving average filter. Since a moving average filter ultimately alters the characteristics of the signal, discretion was used in choosing a suitable sample size of the filter.

In order to determine the frequency content of the signal during small time intervals, a Short-term Fourier Transform (STFT) is performed using 2048 transforms per window, 512 sample window size, and a 256 sample window overlap. The STFT script populates a frequency matrix for each time interval, with a given power level.

In order to determine if the audible data set is a feasible approach to real-time data acquisition and displacement measurement, the mean velocity curve and displacements need to be estimated. In order to determine the mean velocity curve, the following Doppler equation is used, which transforms the shift frequencies into flow velocities:

$$f_D \cong \frac{f_T}{c}\left(2v\cos\theta\right) \qquad (1)$$

where: f_T is the transmitted frequency, c is the speed of sound in tissue (1540 m/s), v is the sample volume velocity, f_D is the Doppler shift frequency and θ is the correction angle.

There are several frequencies (or velocities) present at each moment in time, corresponding to the sample volume size of the moving object. In order to find the mean velocity curve, the mean velocity at each small time interval is calculated. This is achieved by calculating an intensity-weighted mean velocity (IWMV), i.e.:

$$IWMV = \frac{\sum_i V_i p_i}{\sum_i p_i} \qquad (2)$$

where: V_i is the estimated velocity of the i^{th} data point, with a power spectral density of p_i at the time t. The power spectral density was set to be greater than 70 dB to neglect low amplitude noise.

The resulting data set contains the mean velocity of the moving string as a function of time. A cubic spline curve was first fit to this data, and then integrated so that the string displacement can be estimated. In the subsequent section, 20 trials were carried out, comparing our proposed audio based string displacement estimation to both the actual displacements as well as LogicScan's onboard displacement estimation.

III. RESULTS

A. String Displacement Estimation Using LogicScan's Onboard Software

During the 20 trials, the string was displaced by 9.1 cm ± 0.1 cm. Figure 3 shows the resulting velocity spectrogram of the string displayed by LogicScan scanner's onboard software for Trial 1. The onboard software then performed the velocity-time-integral (VTI) to obtain the estimated displacements. The estimated displacements for the 20 trials are shown in Table 2. The mean estimated displacement for these trials was 8.59 cm with a standard deviation of 0.50 cm, in the case of using LogicScan's onboard software.

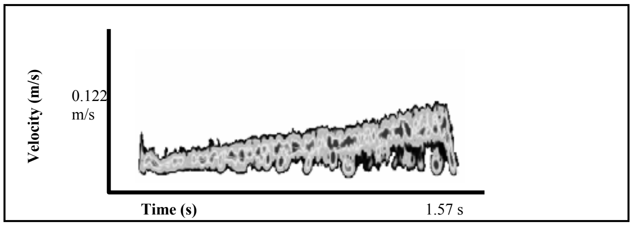

Fig. 3: LogicScan scanner's velocity spectrogram for Trial 1: string velocity vs. time.

Trial No.	Displacement (cm)	Trial No.	Displacement (cm)
1	8.76	*11*	8.65
2	7.47	*12*	8.58
3	7.13	*13*	8.80
4	8.25	*14*	8.80
5	8.50	*15*	8.69
6	8.53	*16*	9.13
7	8.67	*17*	8.72
8	8.73	*18*	8.78
9	8.72	*19*	9.13
10	8.68	*20*	9.17

Table 2: String displacement estimation using LogicScan's onboard software.

B. String Displacements Estimation Using Audio-based Fourier Analysis Technique

For the previous 20 trials, the Doppler-shifted audio signal was simultaneously obtained in real-time using a data acquisition script in Matlab™. The signal was then processed offline (only for the sake of simplicity) in order to determine the feasibility of the proposed techniques. As mentioned earlier, the raw Doppler signal (shown in Fig. 4) contains noise, which was mostly filtered out using a 100-point moving average filter. Using the custom Matlab™ script, the mean velocity points, fitted mean velocity curve and displacements (via integration) were estimated, as shown in Figs. 5 and 6 for Trial 1. Using the proposed technique, the mean displacement was 9.14 cm with a standard deviation of 0.28 cm. The estimated displacements for all 20 trials are shown in Table 3.

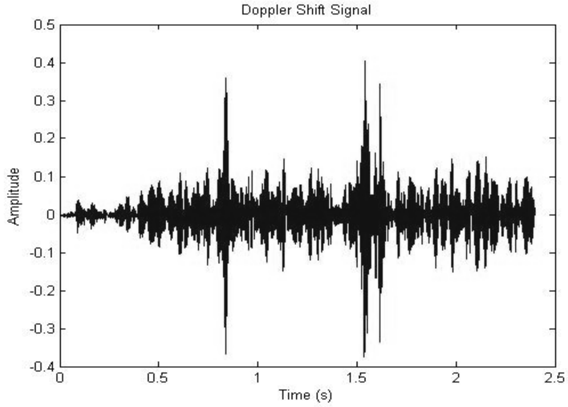

Fig. 4: Demodulated Doppler shifted audio signal.

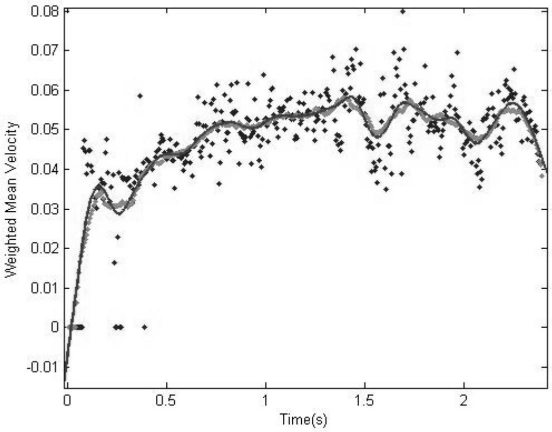

Fig. 5: Mean velocity data points (in m/s) and fitted curve for Trial 1.

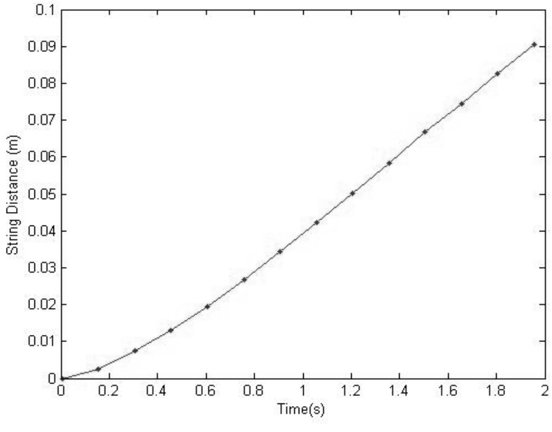

Fig. 6: Integrated mean velocity (i.e. displacement) curve for Trial 1, showing a string displacement of 9.14 cm.

Trial No.	Displacement (cm)	Trial No.	Displacement (cm)
1	9.14	*11*	9.05
2	9.30	*12*	9.22
3	8.40	*13*	9.10
4	8.60	*14*	9.03
5	9.03	*15*	8.93
6	9.60	*16*	9.32
7	9.57	*17*	8.99
8	9.43	*18*	9.08
9	9.24	*19*	9.27
10	9.14	*20*	9.30

Table 3: String displacement estimation using proposed audio-based Fourier analysis technique.

IV. CONCLUSIONS

In this paper, a feasibility study is presented in order to conclusively determine if the real-time Doppler audio from an ultrasound scanner can accurately detect "tendon" motion. By moving a tendon mimicking string 9.1 cm ± 0.1 cm under the LogicScan scanner's transducer, the scanner's software displayed the velocity spectrogram, and the resulting Doppler-shifted frequencies was output and collected as an output signal in real-time. The scanner's onboard software estimated the mean string displacement to be 8.59 cm with a standard deviation of 0.50. These results present poor accuracy and high variability. This is mainly due from the applied Wall Filter which eliminates 7% of the lowest frequencies in the range. This would result in weighting the higher frequencies (and thus velocities), which ultimately affects the outcome of the displacement estimation. Furthermore, the software is calibrated to be used for many different applications, such as imaging deep and surface anatomical structures, fetal imaging and blood flow. Therefore, the types of filters and approximations implemented have to be general enough for these various uses. However, detailed error sources related to these are unknown because the software's approximations and processing methods are proprietary materials for the manufacturer. Furthermore, a fundamental error occurs with the Doppler correction angle. This is because the string flow is not parallel to the ultrasound wavefront. The correction angle was visually determined as 59º. This error appears in both processing techniques when the Doppler equation in Eq. (1) is employed. Therefore, because the string flow was not parallel to the transducer, the correction angle induces an approximate 6% error maximum, in all trials. This 6% error allows the ultrasound's calculated displacements to be within the outer limits of an acceptable range.

In this paper, we showed that the Doppler shifted frequencies of the moving string are also in the audible range and can be transformed into audio signals. This audio signal was obtained in real-time and processed in Matlab™. Using the proposed audio-based Fourier analysis, the estimated mean string displacement was 9.14 cm with a standard deviation of 0.28 cm. These results are quite accurate and within an acceptable range of the actual string displacements.

The successful feasibility study presented here shows that pulsed wave Doppler (PWD) can accurately measure the small velocity and displacements of a moving tendon-like object. Furthermore, real-time Doppler data access from an ultrasound machine is possible by using the audio output. The processed audio has also shown to be more accurate than the ultrasound scanner's software-based results. This new technique will be useful for future work involving real-time displacement monitoring of biological tendons to access hand functions.

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