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HEEL DOWN AND TOE-OFF TIME MEASURED WITH ULTRASONIC
DOPPLER SYSTEM AND FORCE PLATE SENSOR

by
Sabin Timsina

A thesis submitted to the faculty of The University of Mississippi in partial fulfillment of the requirements of the Sally McDonnell Barksdale Honors College.

Oxford, MS
May 2020

Approved by

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Abstract

Collie Box is a medical device that measures the gait parameters of the person walking in front of it. This device uses the Ultrasonic Doppler system to extract the heel-contact and toe-off times of a person walking within the range of 2-10 meters. These times are used to determine the leg's swing phase and double stance times. The ultrasonic transducer of 10mm diameter is driven at 40kHz. At the time of the heel-contact and toe-off, foot velocity is zero while the torso part of the human body is still in motion. The wide directivity of 10mm diameter ultrasonic transducer creates problems in reading the times at which the foot velocity is zero. For processing the received signal, we use Matlab algorithm to fit the measured foot velocity to a model in order to estimate these times. To narrow the directivity of the ultrasonic transducer, different sizes and arrangements of the ultrasonic transducer are compared. The linear array of ten 3.7mm diameter transducer is observed to have narrow directivity. Further, the comparison of the heel-contact and toe-off times is made between force sensor and beamed 3.7mm diameter transducer arrays and single 10mm diameter ultrasonic transducer. As a result, the spectrogram view of unprocessed signal of a person walking in front of the beamed 3.7mm diameter transducer seems to have reduced torso velocity as compared to 10mm diameter ultrasonic transducer. However, when heel-contact and toe-off times of processed signal of a person walking in front of beamed 3.7mm diameter transducer doesn't seem to improve when compared with the force plate sensor.

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Chapter 1

Introduction

Gait is defined as the method of movement from one point to another. A standard gait evaluation requires at least one complete gait cycle, which comprises of heel down of ipsilateral foot followed by heel down of a contralateral and again heel down of ipsilateral foot [3]. Gait analysis plays an important role in improving health condition as it is applied in the rehabilitation and diagnosis of medical conditions and sports activities [4].

Gait can be measured using Acoustic Doppler [5], Camera system [6] and Force Sensing Mat system [7]. Ultrasonic Doppler method can be used to extract signatures of walking human [8]. The gait can be measured using Collie Box, an Ultrasonic Doppler System(UDS) based smart sensor created by UM research scientist Dr. James Sabatier and patented by the University of Mississippi which measures walking speed, leg and torso motion and other movements related to balance and gait [9, 10].

Collie Box uses the ultrasonic transducer to extract the gait parameters. The Collie Box consists of Data Acquisition Board (NI USB6216), a preamplifier and two ultrasonic transducers (transmitter and receiver). Collie Box transmits 40kHz signal using NI USB 6216 Data acquisition board and ultrasonic transmitter. The Doppler shift signal is reflected back from the human in motion and is received by

ultrasonic receiver followed by preamplifier and NI USB 6216 Data acquisition board respectively. The data collected are processed using the Matlab image processing code developed by Jeremy Webster, an employee of SOAIR. After processing, the code gives results of gait parameters including stance time, swing time and double stance time. The representation of heel-down and toe-off times can be seen in Figure 1.1. The red-colored leg shows instances of heel down and toe off.

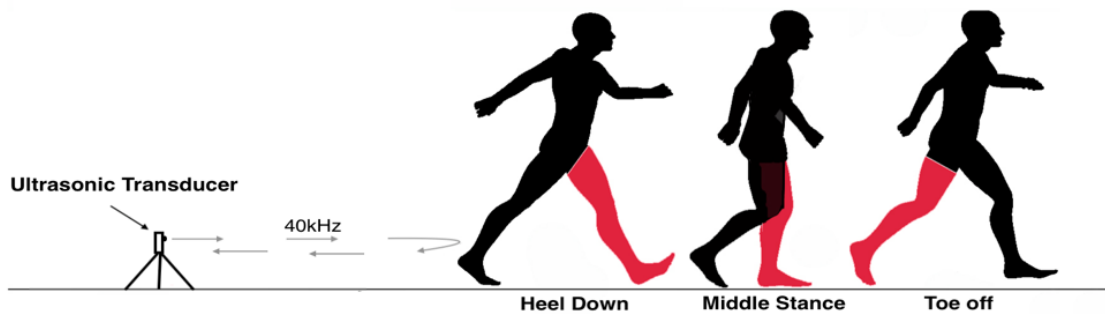


Figure 1.1: Representation of Heel Down and Toe off. Source: [1]

This thesis describes the comparison of heel-down and toe-off time measured by the Collie Box and force plate sensor. The procedure for measurement of heel-down and toe-off time can be seen in Figure 1.2. The force plate sensor is considered to give ideal results for heel-down and toe-off time which is from Force Sensing Resistors family.

For the experiment, the combined version of the first and second generation of Collie Box is used. From the first generation, pre-amp and ultrasonic transducer is used and from the second generation, data acquisition board and processing software are used for the experiment [11]. The main reason for using the combined version of the first and second generation is because of the high quality of components used in the older version. Also, because of the convenient way of editing software and extracting



Figure 1.2: Collie Box

data in the older version. In the first and second generation of Collie Box, high-quality amplifier and multi-functioning data acquisition board was used. The use of such components helps in acquiring accurate data. Also, the software designed for the second generation Collie Box was more convenient to edit which can ultimately help in comparison of data among ultrasonic transducer and force plate sensors.

Chapter 2

Software Used

Collie Box's operation is divided into two different parts i.e. Data Acquisition and Data Analyzer. Two different software are used for the execution of each function.

2.1 EchoGT_trig.exe(Labview)

EchoGT_trig.exe is a software designed by Jeremy Webster for Collie Box's data acquisition process. This software based on the LabVIEW platform is an executable file that is specially designed to operate NI's Data Acquisition Board (USB 6216). This executable file is designed for both technical and non-technical users for a convenient way of collecting data. The software has a user-friendly interface where users have access to change file location, input voltage range and running time interval. This compiled version of LabVIEW code can generate and acquire signals using NI USB 6216. The acquired signals are further processed with in the software and the outputs are saved in “. d” file.

2.2 EchoWalkAnalyzer.exe(Matlab)

EchoWalkAnalyzer.exe software is responsible for the analysis of the collected data. This software-based on Matlab platform was also designed by Jeremy Webster. This executable version of Matlab has been made by focusing on all kinds of users from different backgrounds. The good user interface of this software allows users to easily select a specific walk and obtain the gait parameters for that specific walk. The output gait parameters mainly include mean peak foot velocity, mean stance time, mean stride length, mean gait speed, mean swing/stance ratio, step cadence and a few more along with the option to view the 3D graph of the walk. The software is optimized for reading the data saved by EchoGT_trig software and processing the data using the Image processing algorithm.

Chapter 3

Hardware Used

3.1 NI USB6216(DAQ board)

National Instruments' DAQ board is a multi-functioning device that is capable of both input and output of analog and digital signals. This device can support up to 16 analog input channels along with the ADC resolution of 16 bits and sampling rate of 400KS/s on aggregate. Furthermore, this device supports 2 output channels with DAC resolution of 16 bits at maximum update rate of 250KS/s per channel [12].

As a result of its sufficient capacity of I/O signals, this device was used in Collie Box. This device needs to be connected to a computer for its execution. The LabVIEW program gives instruction to the device. In the context of Collie box, this data acquisition device is used to generate 40 kHz signal and acquire signals at a sampling rate of 100 kHz.

3.2 Ultrasonic Transducer

The Collie Box used two ultrasonic transducers which can drive 40 kHz frequency. Among the two of them, one is a transmitter and another is a receiver. The transmitter is noted by a letter "T" in the back of transducer whereas the receiver is noted

by a letter “R” in the back of transducer. The size of the vibrating surface in both transmitter and receiver is 10 mm.

3.3 Pre-Amplifier for Ultrasonic Transducer

The Collie Box uses a pre-amplifier made by Analog Modules INC with a gain of 200. This pre-amplifier is integrated inside the Collie Box. As for the experiment, we decided to use a better version of amplifier which is Stanford Research Systems (SR560). This particular amplifier has many features that are useful while carrying out experiments. Features including variable gain setting (1 to 50000), High pass and Low pass filter, AC/DC coupling and overload indicator are supposed to help during the process of acquiring Doppler shift signals. These merits encouraged us to use SR560 instead of integrated Analog Modules INC’s pre-amp

3.4 Force Sensitive Resistor

The sensor made by Interlink Electronics was used for testing the accuracy of the device. The Force Sensitive Resistor is long with a sensor dimension of 609.22 x 5.08mm. This sensor can sense the force applied by an object of mass 0.1N to 10N. The force is measured by varying its resistance depending on the pressure applied [2].

Chapter 4

Working principle: Data Acquisition

The general work-flow of Collie Box can be seen in Figure 4.1. Collie Box's working procedure can be divided into Data Acquisition and Data Analyzer. The data acquisition process is related to signal generation and acquisition.

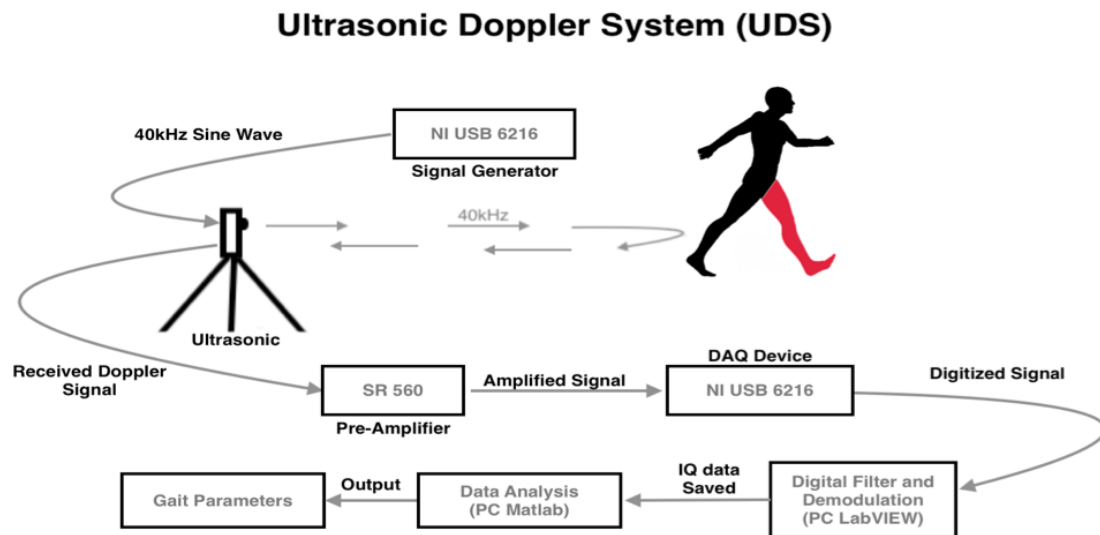


Figure 4.1: Representation of Working procedure. Source: [1]

Data acquisition in Collie Box is the process of acquiring the Ultrasonic Doppler signals using NI USB 6216 device. At first, 40 kHz sine wave is generated from NI device. The generated signal is then connected to the ultrasonic transducer for emitting 40 kHz sine wave. The emitted sound wave gets reflected from the human body in motion. The reflected signal is then received by the ultrasonic transducer and then amplified and transmitted to NI device for Analog to Digital Conversion (ADC). The LabVIEW processes the data obtained by NI device and passes it through the filter. Finally, the obtained I and Q signals are saved in “.d” file. The detailed explanation of the working procedure can be explained in the following steps:

4.1 Signal Generation

The signal is generated by NI USB 6216 device. The information of the output signal is passed to NI device through LabVIEW. The signal generated by the NI device is a 40 kHz “sine wave” signal. In our case, the analog output channel used is “AO 0”.

While generating 40 kHz sine wave, the following information needs to be passed to signal generation function “Sine Waveform VI”.

a Frequency: 40 KHz

b Amplitude: $\pm 10V$

- Max Value: Maximum output voltage for the Device. In our case its 10V.
- Min Value: Minimum output Voltage. In our case its -10 V.

c Sampling Info: Sampling Information needed for generating the output. It consists of following parameters:

- Sampling rate: 100000 Hz is used as sampling frequency for the output signal.

- Number of Samples: 2500 samples is generated.

Once the parameter is passed, sine wave of 40kHz is generated by the NI device. The generated wave is then transmitted by the ultrasonic transducer. Further, within the LabVIEW, the digital sine wave of 40kHz is generated and passed to “Filter And Demod.vi” sub vi for demodulation process.

The transmitted analog signal is reflected from the human body and is received by the ultrasonic transducer. The received signal is amplified with a gain of 200. The amplified signal is then passed to NI data acquisition device. In our case, the analog input channel used is “AI 6”. Also, the duration of the signal to be acquired can be controlled with “Timer” function.

While acquiring signal, the following parameters and value are passed to the Analog Voltage and Analog read function:

a Input Voltage Range: The default voltage range is 5V.

b Sampling Info : $\pm 10V$

- Sampling Rate: 100000 Hz is used as sampling rate of Input signal
- Number of Samples: 2500 samples are acquired in each loop execution.
- Coupling: The coupling mode is set for DC coupling.
- Sampling Mode: Sampling mode is set to Continuous Sample mode. Sample is collected until the Data acquisition is stopped.[13]

4.2 Fliter

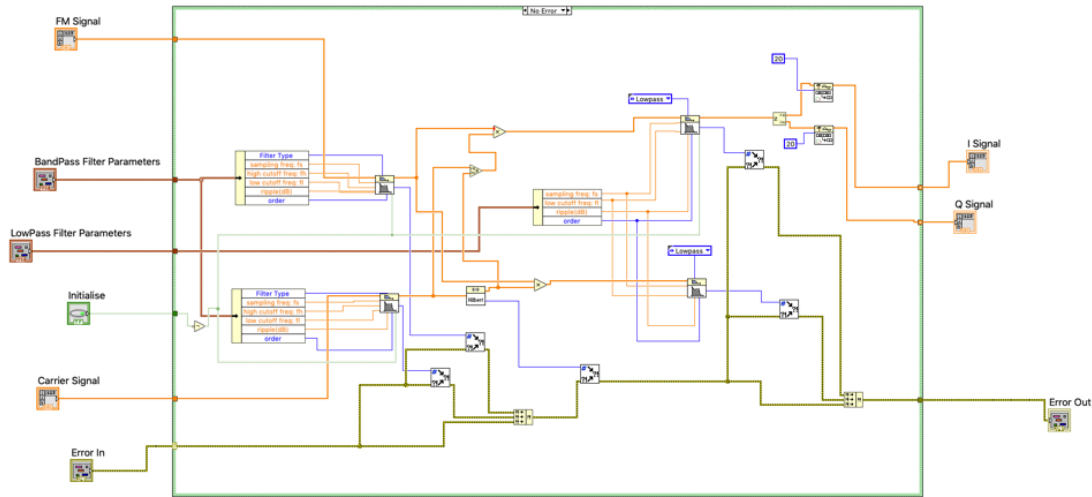


Figure 4.2: Diagram of “Filter And Demod.vi”, designed by SOAIR

The acquired signals (FM signal) and parameters are passed to sub vi “Filter And Demod.vi”, which can be seen in Figure 4.2. This function process the signals which are based on parameters that are passed. The parameters that are passed are explained below.

4.2.1 Band Pass Filter

The main function of bandpass filter is to allow signals of specified range of frequency and block out the signals with frequencies higher and lower than the specified range. Most important parameters passed to band-pass filters are:

- a Sampling Frequency:100000Hz
- b High Cut Off Frequency: 42500Hz
- c Low Cut Off Frequency: 37500Hz

4.2.2 Low Pass Filter

The low pass filter allows signals below the mentioned frequency to pass through it. In our case, the signals below 2000 Hz can pass through the filter. Two important parameters passed to the low pass filter are:

- a Sampling Frequency:100000Hz
- b Low Cut Off Frequency: 2000 Hz

4.3 IQ Demodulation

The bandpass filter allows signals between 37500Hz and 42500Hz to pass. The signal passed through the bandpass filter is multiplied with the complex number which is formed of the carrier signal as a real number and Hilbert transform of the carrier signal as an imaginary number.

According to Asif Mehmood [8], multiplication is done to demodulate the FM signal by converting the FM signal into baseband I(t) and Q(t). It can be expressed mathematically as:

$$g(t) \cdot g_c = 1/2[\cos(4\pi f_c t + \phi) + \cos(\phi)] \quad (4.1)$$

where f_c =carrier frequency, $g(t)$ is the FM signal and $g_c(t) = B\cos(2\pi f_c t)$ which is synthetically generated.

$$g(t) \cdot g_{co} = 1/2[\sin(4\pi f_c t + \phi) + \sin(\phi)] \quad (4.2)$$

where $g(t)$ is the FM signal and $g_{co}(t) = B\cos(2\pi f_c t - \frac{\pi}{2}) = B\sin(2\pi f_c t)$ which is synthetically generated.

Once the signal is passed through the low pass filter, complex number is converted

to two numbers followed by the decimation factor of 20. The real part of the complex number can be obtained as

$$I(t) = \cos(\phi) \quad (4.3)$$

The imaginary part of the complex number can be obtained as

$$Q(t) = \sin(\phi) \quad (4.4)$$

The resultant baseband signals $I(t)$ and $Q(t)$ are then saved to a “. d” file.

$$S(t) = I_{dec}(t) + iQ_{dec} \quad (4.5)$$

The signal can be represented as $S(t)$ $I_{dec}(t)$ and iQ_{dec} represents decimated $I(t)$ and $Q(t)$ respectively. The velocity of human body can be computed using spectrogram, square of short-time Fourier Transform (STFT) and can be expressed as:

$$STFT(t, f) = \int S(t + \tau)w(\tau)\exp(-j2\pi f\tau)d\tau \quad (4.6)$$

where $S(t)$ is the complex down-converted signal, $w(\tau)$ is sliding window function, “t” is time and “f” is frequency [8].

Chapter 5

Working principle: Data analyzer

The data analyzing of Collie Box is performed by the software “EchoWalkAnalyzer.exe”. This software is based on Matlab platform and is designed to work on PC. The software reads the file containing IQ data saved by data acquisition software. The obtained raw data is processed using image processing algorithms and at the end, the values of gait parameters are calculated. “EchoWalkAnalyzer.exe” software is compiled of different Matlab functions each dedicated to specific tasks. The stepwise description of the data analyzing process is explained below along with the reference to the Matlab functions.

5.1 Data read

Once the main function is executed it calls the function “opcCSVREAD.m”. The main work of the “opcCSVREAD.m” function is to read IQ data from “.d” file saved by data acquisition software. The “opcCSVREAD.m” function takes in two different parameters which include “filename” and “debug”. ‘Filename’ is the name of “.d” file and ‘debug’ is the boolean value. These two parameters are provided by the main function.

The function extracts two columns of $I(t)$ and $Q(t)$ data from the file. The ex-

tracted data are passed through code referenced from the ‘myspectrogram’ function to calculate velocity, time and short-time Fourier Transform(STFT) of the data. The STFT is further used for finding the intensity of the reflected signal. This can be done by finding the absolute value of the function. The function “myspectrogram”, developed by SOAIR is similar to the “spectrogram” function, which is an inbuilt function in Matlab. Once the velocity, time and STFT have been calculated, values are returned back to the main function for further processing.

5.2 Normalizing the walk orientation

The raw data are passed through lines of code to find if the person is walking towards the Collie Box or away from the Collie Box. Once the walking orientation is figured out, further processing is done to make all the walks look similar. All walks are normalized using the following standards:

- a All spectrogram (3D color graph) should always begin with Doppler shifted signals closest to the Collie Box and end with Doppler shifted signals farthest from the Collie Box.
- b The spectrogram (3D color graph) should be aligned so that zero Doppler shift corresponds to zero velocity and higher Doppler shifts should correspond to higher positive velocity [14].

5.3 Process of Normalizing walks

- a **When a person is walking away from the Collie Box:**

The data is flipped vertically. When the person is walking away, all velocities are in negative. So, to make every data look similar for easier further processing,

data is vertically flipped. Here is the example represented by Figure 5.1 and Figure 5.2.

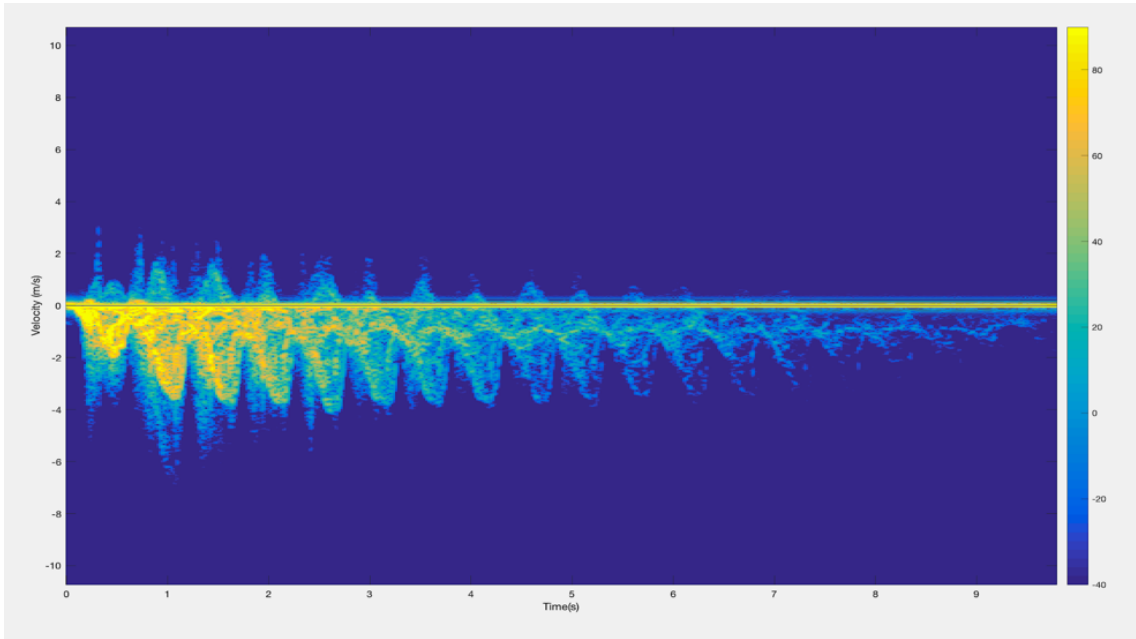


Figure 5.1: Walking away from the Collie Box, Unprocessed Data

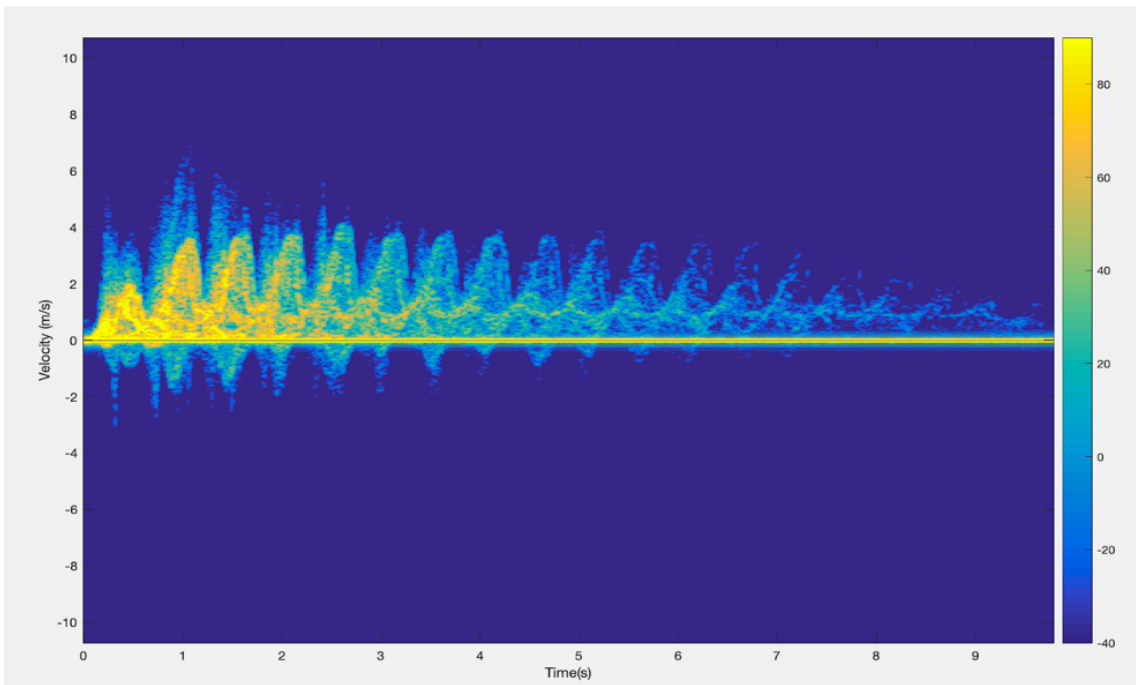


Figure 5.2: Normalized walking orientation

b When a person is walking towards the Collie Box:

The data is flipped horizontally from right to left. The Doppler shifted signals obtained from the closest distance to the Collie Box are located around the end of the time frame. So, the Doppler shifted signals to the end is flipped and brought to the beginning of the time frame to make further processing easier.

5.4 Removal of the bottom half from the Graph

In this step, data in the bottom half of the spectrogram is removed as it is no longer needed. This is done because all data containing Doppler shift signals are shifted to the top half. This led the bottom half with mostly noise. Removing the noises on the bottom half makes further processing easier and efficient.

5.5 Image Contrast adjustment

At first, the spectrogram is converted into gray color which normalizes the range of intensity from 0 to 1. Then the intensity of velocity which is near to “0 m/s velocity” is suppressed. This is done so that the high-intensity velocity, consisting of mostly noise, near 0 m/s won’t affect while finding the envelope. In the further codes, envelope is found with the help of analyzation of maximum intensity of velocity. Noise present near the 0 m/s obstructs in finding accurate envelope. This is done by suppressing the intensity of velocity from 0 m/s to 0.4 m/s. This can be seen in Figure 5.3. Without removal of intensity from this range of velocity, it would be highly difficult to produce accurate results.

After the suppression of intensity from the range of velocity, data are then passed through the “weiner2” filter and then through the “imadjust” function. These two function helps to refine and adjust the contrast of the gray image. The “weiner2” filter helps to remove noise in the image [15].

The “imadjust” function helps to adjust the contrast throughout the whole image. It further helps to adjust dissimilarities in the intensity of velocity and reduce the background noise [16]. This can be seen in Figure 5.4. These steps are repeated twice to produce a more refined image with adjusted contrast. The two different functions have their applications.

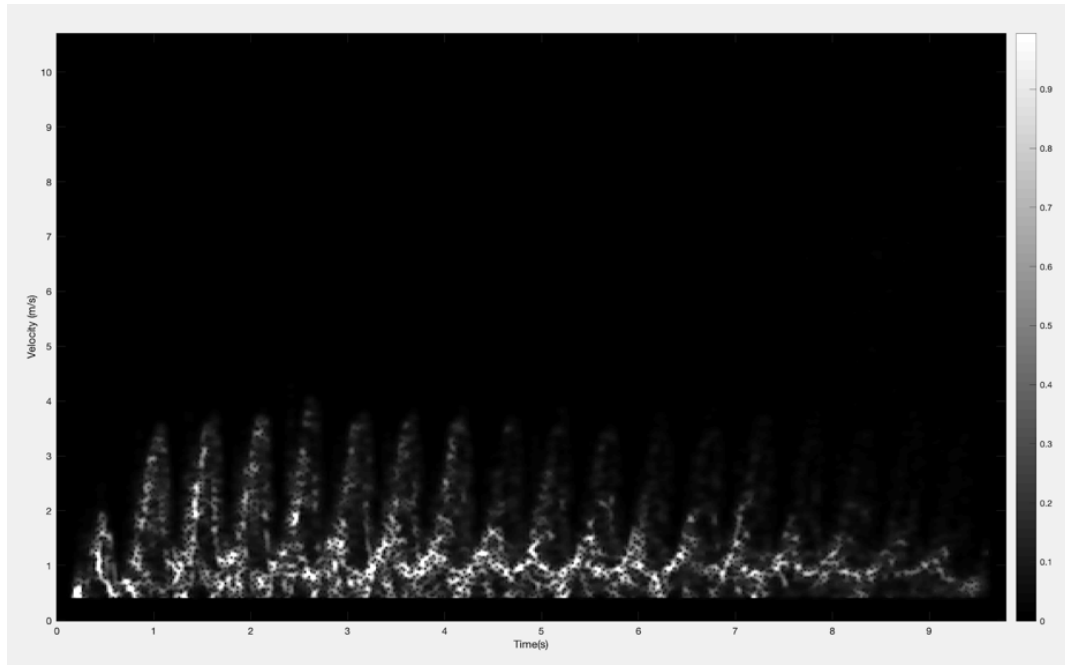


Figure 5.3: Intensity is suppressed up to 0.4m/s after passing through weiner2 Filter

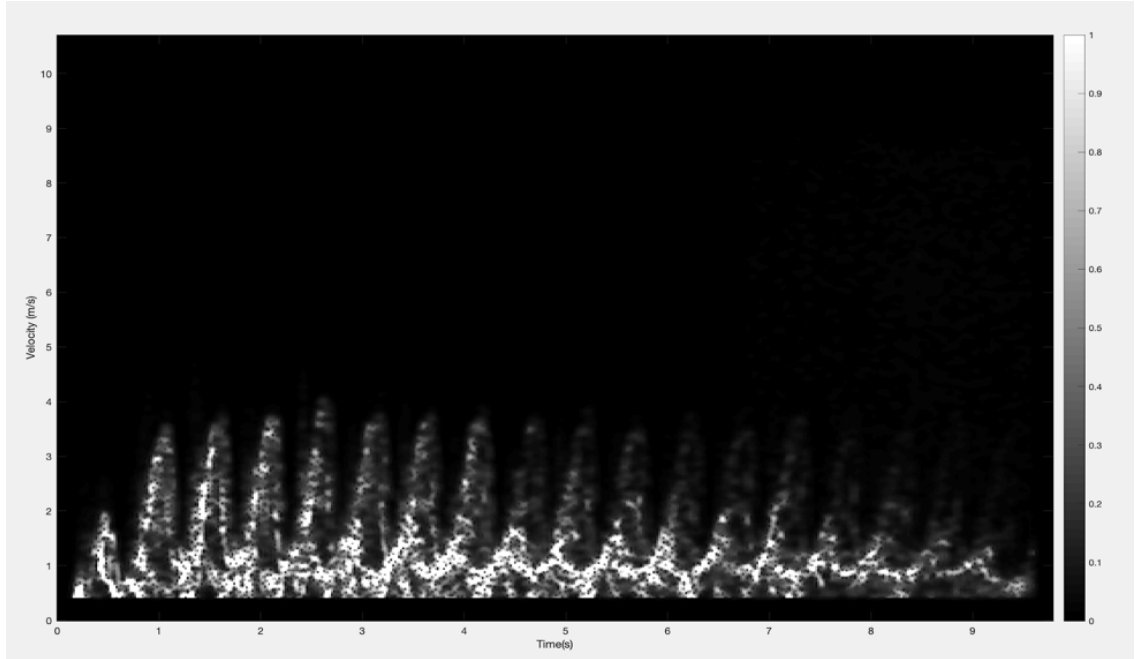


Figure 5.4: Plot obtained after passing data through imadjust function

5.6 Restoration of Contrast

Once the data are passed through the “restoreContrast” function, it forces the image to take up that entire range i.e. to have the highest contrast possible. This is done by first forcing the smallest pixels to zero and then normalizing the rest of the pixels so that the brightest pixel will be 1 [14].

5.7 Finding the Envelope

At first, three different variables “rows”, “tvals” and “border” are initialized. The threshold intensity is determined to be 0.2. The maximum intensity at a single time point is found and if the maximum intensity is less than 0.2 then all the velocity points present the specific section of time is considered to be noise. After that, a condition is set so that the maximum intensity is 1000 only if the maximum value is less than 0.2. If the maximum intensity is greater than or equal to 0.2 then maximum

intensity is left as normal.

The determined maximum value at each time frame is then multiplied with the threshold value. After that, while loop execution is performed in decreasing order from the highest velocity to lowest velocity. Here the “while loop” loops through each velocity inside a for loop which loops through time. When the “while loop” goes down from peak velocity to low velocity and whenever intensity of velocity is found to be greater than the considered noise level (tvals), the velocity point is picked and stored. This process continues until it finishes the same process for 490 time points. In the end, it loops through 490 time points and collects the outer signal level for all time points. The envelope of Figure 5.4 can be seen in Figure 5.5.

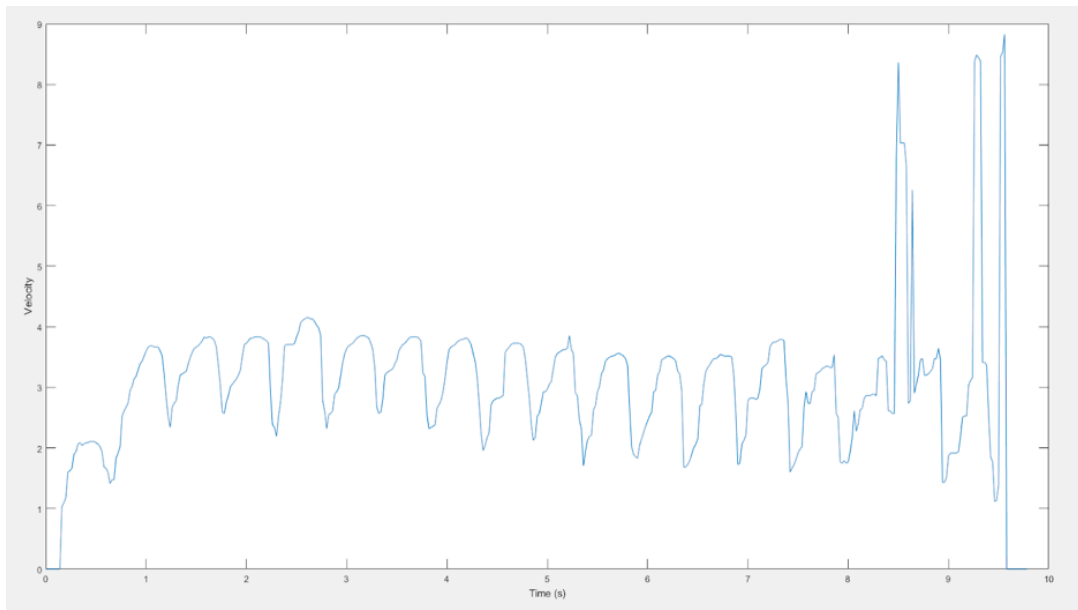


Figure 5.5: Envelope of Figure 5.4

5.8 Smoothing Curve

Once the envelope is found, the smoothing of the curve begins. For this, the data are passed through the “medfilt1” function. This function acts as a median filter. It takes median between two points and makes the curve smoother and removes noise

present in it [17]. The data is again passed through the “smooth” function which smoothens the curve. The smoothed curve can be seen in Figure 5.6.

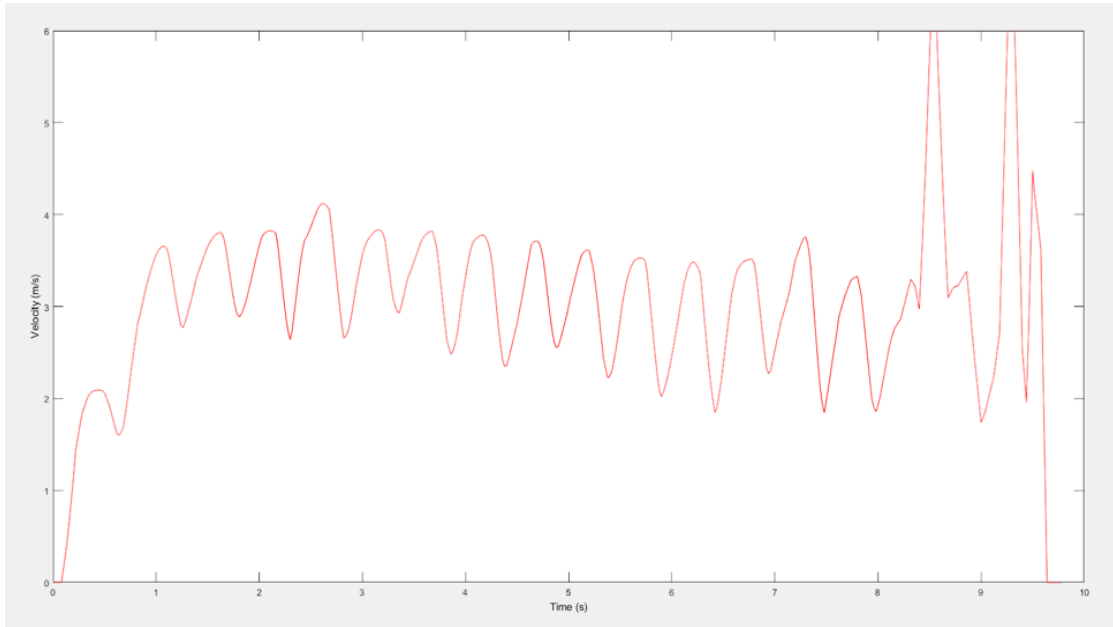


Figure 5.6: Applying ”medfilt1” and ”smooth” function to envelope in Figure 5.5

5.9 Finding peak velocity for each leg swing

For the process of finding peaks, “findpeakx” function is used. This function finds the highest velocity point (peak) for each leg swing. Then it picks the value of the highest peak and its position in the time frame. This can be seen in Figure 5.7. It stores the peak value and position of the peak. Further, this function takes 7 parameters as input. The input parameters are shown along with the function:

```
findpeakx (x, y, SlopeThreshold, AmpThreshold, smoothwidth, peakgroup, smoothtype)
```

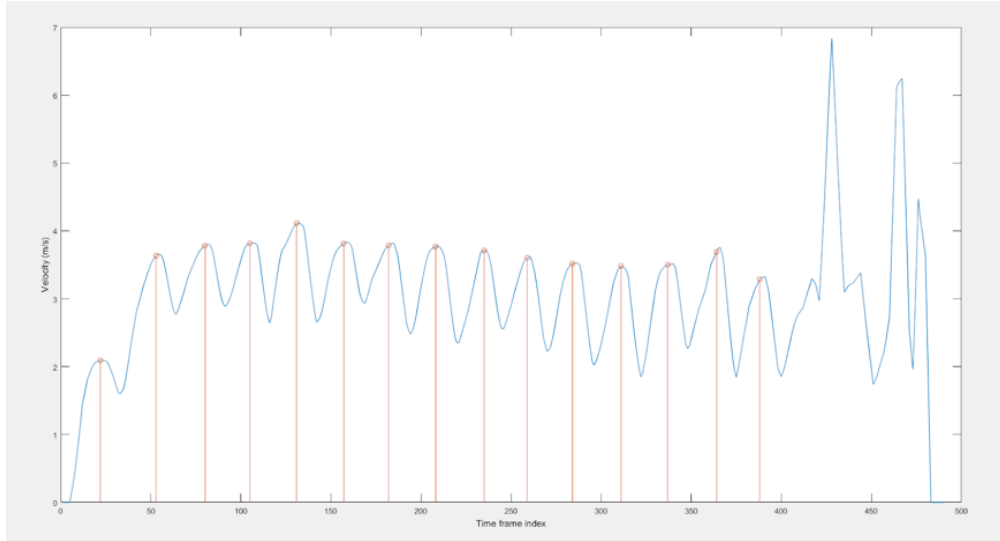



Figure 5.7: Peak of each Leg Swings(Stride)

5.10 Finding good peaks

After finding the peaks, it is necessary to figure out the good peaks and their location in the time frame. The good peaks are determined by the velocity level of the peak. If the peak velocity falls between 1 and 5.5 then it's a good peak. Once the good peak is determined then peak value and location of good peaks are stored.

5.11 Determining if there is stride

If the number of good peaks is resulted as "0" then there is no strides. Number of strides is the total number of good peaks. After figuring out the number of good peaks, the number of strides can be found.

5.12 Skipping stride on start and end

Once it is determined that there are strides, the next step to skip some strides at the start and the end. This is done because the first step while starting and last step

while stopping don't indicate the normal walk of the person. When a person starts or stops to walk, velocity is very low compared to normal walking speed. So to get more accurate parameters, steps on start and end are skipped. This is done by removing first and last peaks from the variable containing peaks.

5.13 Picking top Portion of Graph

Once the good peaks are found then the program steps forward for finding the nature of each curve. For this, it picks the peak value and its location coordinates(index) of each peak. Then the program tries to find the beginning and ending index of each curve. It goes equal distance from the peak on either side to find its nature. When it determines the ending and starting of the curve on each side, the value and the index are stored. In this process, the top portion of the curve is selected. In the program, it is coded to go 9

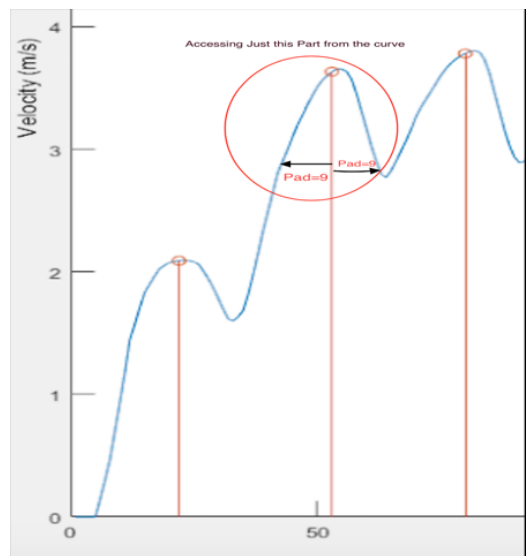


Figure 5.8: Picking the Selected portion

index forward and 9 index backward from the location of the peak to find the curve's nature, which can be seen in Figure 5.8. The value of 9 is calculated after analyzing a series of walk swinging patterns. This program runs the same process for every peak and determines the nature of each curve.

The main purpose of finding the nature of the curve is to reproduce a new curve of the same nature so that the newly formed curve can provide the heel-down and toe-off time. Thus, the obtained value will further help in the calculation of gait.

5.14 Curve Fitting: Gaussian and Cosine curve fitting

The main purpose of Gaussian Fitting is to get the amplitude of the curve which can be further used in Cosine fitting and while reproducing the new curve model.

The purpose of cosine fitting is to find the phase and period of the curve which is going to help in reproducing the new curve model.

Once the nature of the curve is resolved then the program tries to fit a curve at each peak. For the fitting, the program uses “gaussFit” function. This function uses the starting, ending, and the peak of each curve along with their time index to fit a Gaussian function. The Gaussian fit is performed for each curve. The Gaussian distribution function can be represented as [18]:

$$f_g(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \cdot e^{-\frac{(x-a)^2}{2\sigma^2}} \quad (5.1)$$

where “a” is mean and σ is the standard deviation.

Once the Gaussian function is fitted, it gives three different components as “ a_1 ”, “ b_1 ” and “ c_1 ”. Comparing the given function with the Gaussian distribution formula we can represent as:

$$a_1 = \frac{1}{\sqrt{2\pi\sigma^2}} \quad (5.2)$$

$$b_1 = a \quad (5.3)$$

$$c_1 = \sqrt{2}\sigma \quad (5.4)$$

where “ a_1 ” is amplitude of the Gaussian function, “a” is average and σ is the standard deviation.

After storing the amplitude of the Gaussian function, the cosine fitting is carried out. For cosine fitting, the function named “cosFit3” is used. This function uses the amplitude and value of “1/c1” obtained from Gaussian function along with the value and time index of the starting, ending and the peak of each curve to fit a cosine function. The Cosine function can be represented as [14]:

$$c_1 = A\cos(Bx + c) \quad (5.5)$$

where,

A is Amplitude

$-\frac{C}{B}$ is Phase

$\frac{2\pi}{B}$ is Period

5.15 New curve model

The new Cosine function is constructed using the amplitude from Gaussian fit function and phase and period from cosine fit function. The absolute value of the cosine function is then multiplied with the “boxcar” to find the right fitting curve for each leg swing.

5.15.1 Main Function of ”boxcar”

When while loop runs through every peak, it creates many cosine waves at the end of the process. However, each cosine wave is designed to fit just one stride (leg swing). So, boxcar sweeps through time and makes half cosine wave to fit for just 1 specific leg swing for which it was designed. It will remove the rest part of cosine waves which are not in the range of the specific leg swing. The curve before passing through boxcar can be seen in Figure 5.9 and the curve after passing through boxcar can be

seen in Figure 5.10.

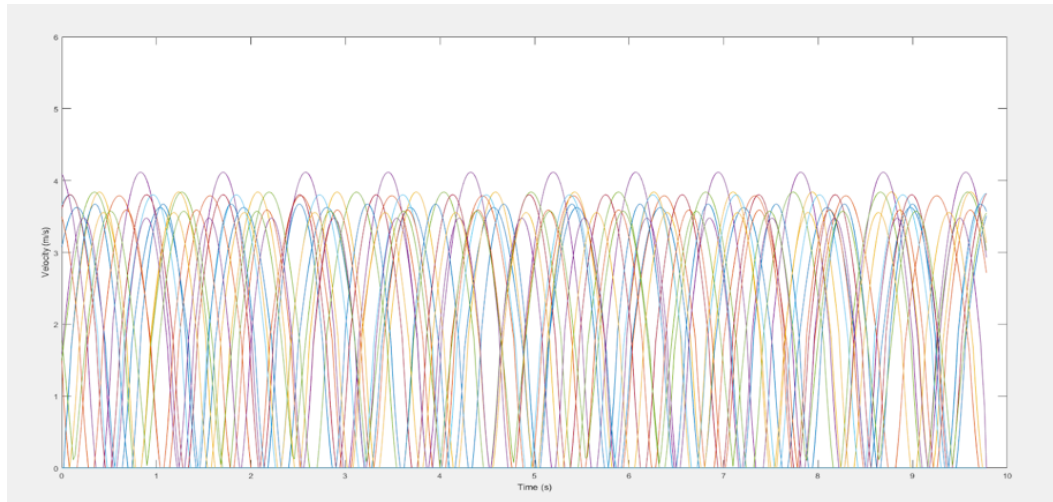


Figure 5.9: Cosine wave for all 12 leg swing before multiplying by boxcar

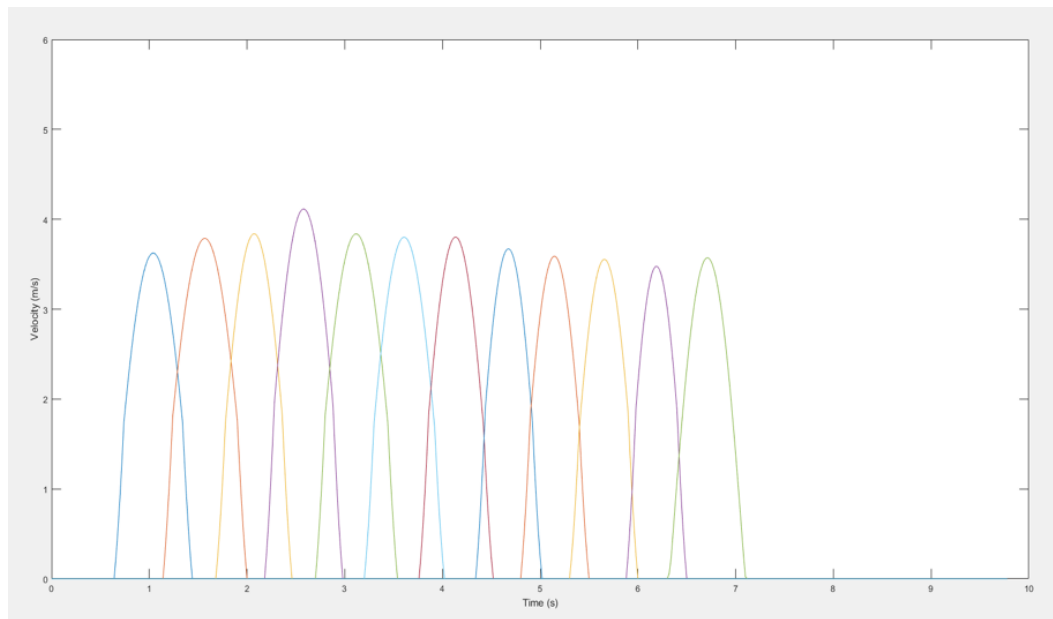


Figure 5.10: Cosine wave for all 12 leg swing after multiplying by boxcar

5.15.2 Matching with results of Vicon

Vicon cameras collect motion data to perform Real-time Gait analysis. In this real-time gait analysis platform, patients walk on a treadmill while Vicon cameras collect motion data. The treadmill can run in a self-paced which allows the subject to walk

naturally while placed in a speed-matched Virtual Reality (VR) environment with 180° field of view projection [19]. While testing “Collie Box”, the results of “Vicon” are supposed to be ideal.

The new model curve is designed so that it matches the curve of Vicon. Figure 5.11 shows the “Collie Box” results matching with “Vicon” results.

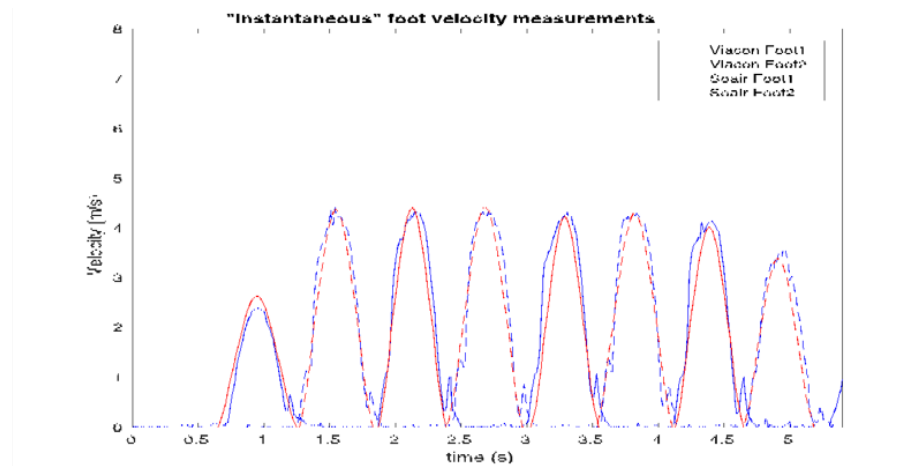


Figure 5.11: Fitting of Collie Box Data with Vicon Data

In the process of making the result of “Collie Box” to match with the result of Vicon, the resulted new cosine wave is multiplied with the square of Gaussian function. The newly formed Gaussian function is a modified version of the Gaussian fit function of each leg swing. The modification made while reforming the Gaussian function includes “Standard Deviation” being multiplied by a constant of 0.7 in newly formed Gaussian function so that the curve matches the results of Vicon.

The reason cosine wave is multiplied with the square of Gaussian function is because the cosine wave is wider and doesn’t fit well with the legs swings data obtained from Vicon. After multiplying by the square of the Gaussian function, the curve becomes leaner at the bottom and seems to fit with data obtained from Vicon. The curve before and after multiplying by the square of Gaussian function can be seen in Figure 5.12 and Figure 5.13 respectively.

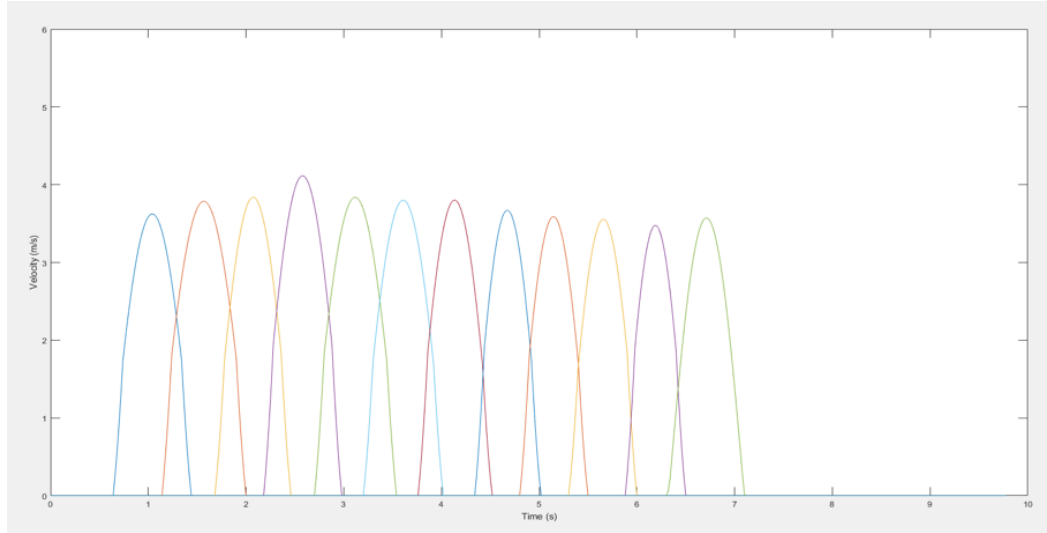


Figure 5.12: Cosine wave for 12 leg swing before multiplying by $(\text{Gaussian Function})^2$

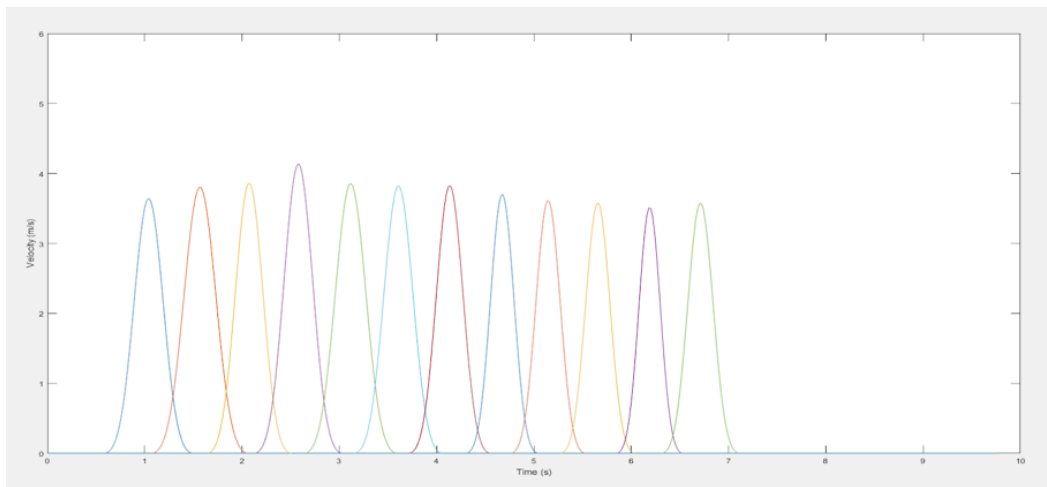


Figure 5.13: Cosine wave for 12 leg swing after multiplying by $(\text{Gaussian Function})^2$

5.15.3 Making Lower velocities smoother to fit Vicon

Since the curve is broad in the bottom part, removing the bottom portion is the best way to produce more accurate results. So, if the velocity value is less than 30% of the peak velocity then velocity is set to zero.

To make the curve fit more with the results of Vicon, smooth function is applied to the curve so the lower part of the curve fits with the curve from Vicon. The curve

before and after applying smooth function can be seen in Figure 5.14 and Figure 5.15 respectively.

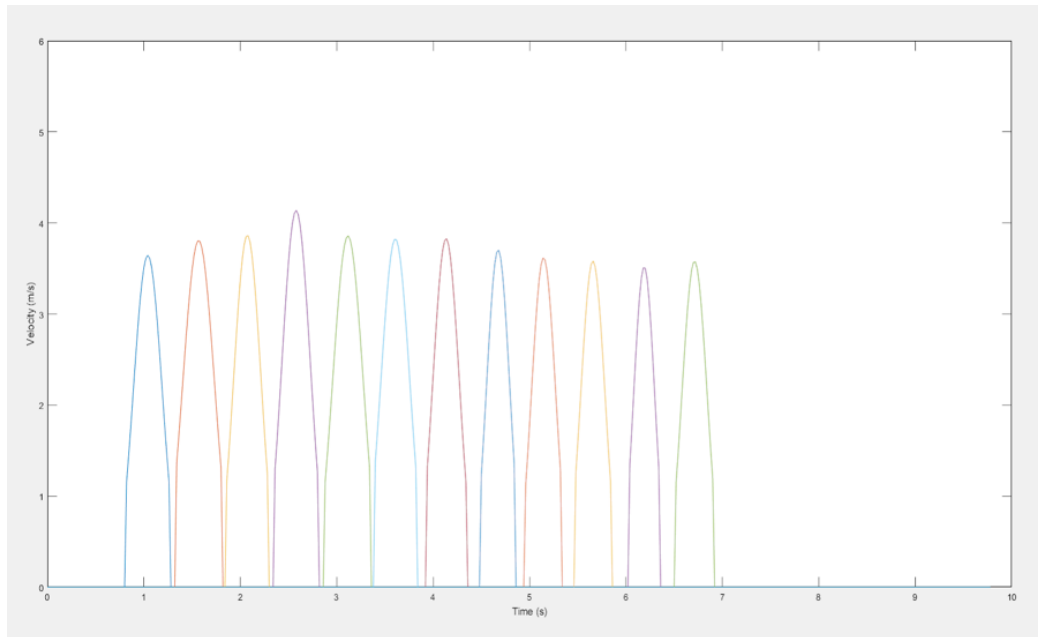


Figure 5.14: Cosine wave for 12 leg swing before applying smooth function

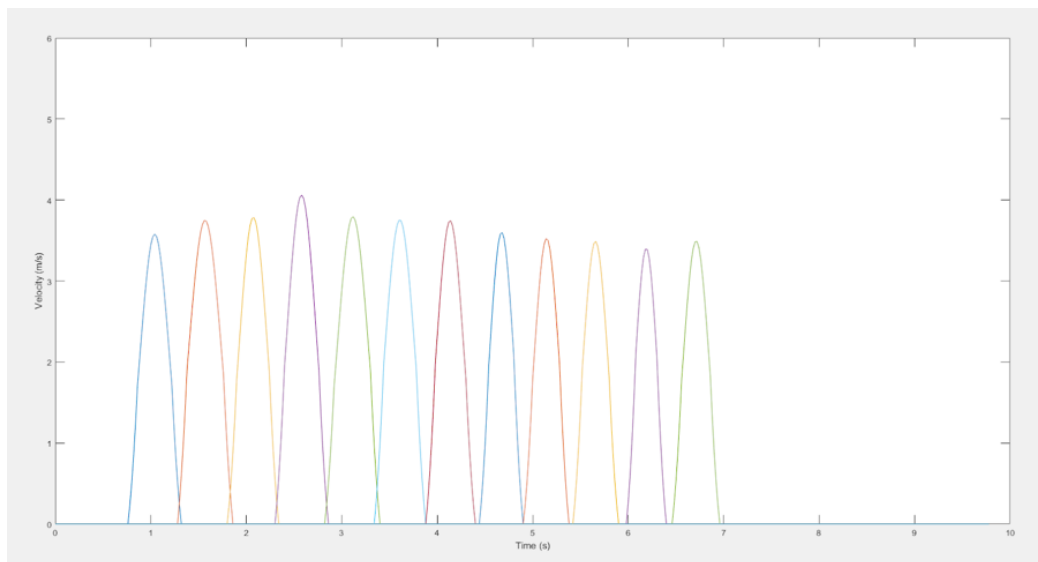


Figure 5.15: Cosine wave for 12 leg swing after Applying smooth function

5.16 Receiving Gait Parameters

The modeling of the curve is completed after matching with the results of Vicon. After that, further processing is done to extract the heel-down and toe-off time along with the velocity of the walk. For this, all the walking data is passed through the “gaitparameters” function along with the difference between each time frame “dt”. All the gait parameters except the peak velocity and cadence depend upon the time of heel down and toe-off time. The “gaitparameters” function then returns all parameters values. Figure 5.16 below shows the physical details of the normal walk:

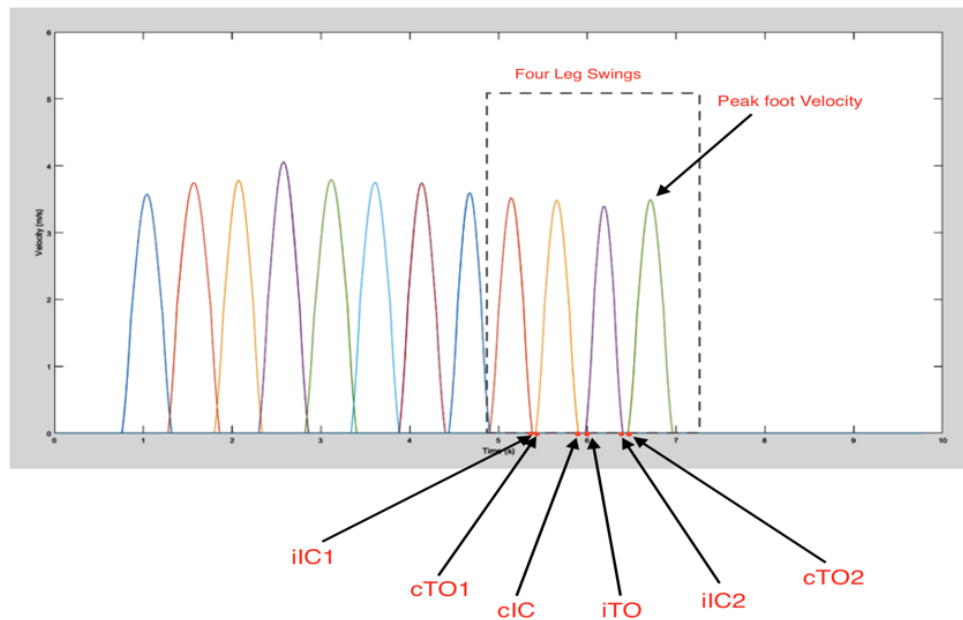


Figure 5.16: Leg swings along with markings of Heel down and toe-off Times

Based on Jeremy Webster [14] and Chenye Li [11], different gait parameters can be represented and calculated as:

- **Peak Foot Velocity** - maximum velocity of a foot during a step
- **Stride time** - Duration from iIC1 to iIC2
- **Stance time** - Duration from iIC1 to iTO of a stride

- **Swing time** - Duration iTO to iIC2
- **Swing/Stance Ratio** - Swing time percent divided by stance time percent
- **Initial Double Support time** - Duration from iIC1 to cTO1
- **Late Double Support time** - Duration from cIC to iTO
- **Single Support time** - Duration from cTO1 to cIC
- **Step tim** - Duration from cIC to iIC2
- **Step cadence** - Number of steps per minute
- **Foot velocity** - (Stride Length)/(Swing time)
- **Peak Foot velocity** - highest foot speed measured during a step
- **Stride length** - foot displacement from iIC1 to iIC2
- **Stride velocity (Gait speed)** - (Stride length)/(Stride time)
- **Stride cadence** - Average over left and right cadences
- **Gait Speed** - stride length/stride time
- **Walk Ratio** - step cadence/mean stride distance [14, 11].

The major gait parameters among these are briefly described below:

5.16.1 Swing time

Swing time is the time interval when the foot leaves the ground (toe-off) and again touches the ground with the same foot (heel-down). From the Figure 5.16, Swing time can be measured as “cIC - cTO1” [3].

5.16.2 Stance Time

Stance time is the time interval between the foot touching the ground (heel-down) and the same foot leaving the ground (toe-off). From the Figure 5.16, Stance Time can be measured as “iTO-iIC1”.[3]

5.16.3 Double Stance Time

Double Stance time is the time interval when both foot are on the ground in a gait cycle. Since both foot are on the ground, the velocity of the foot is zero during the double stance. From the Figure 5.16, Double Stance Time can be measured as “cTO1-iIC1”.

After the completion of processing, the new curve is fitted over the spectrogram of the normalized walk which can be seen in Figure 5.17. Also, the values of gait parameters can be seen in Figure 5.18.

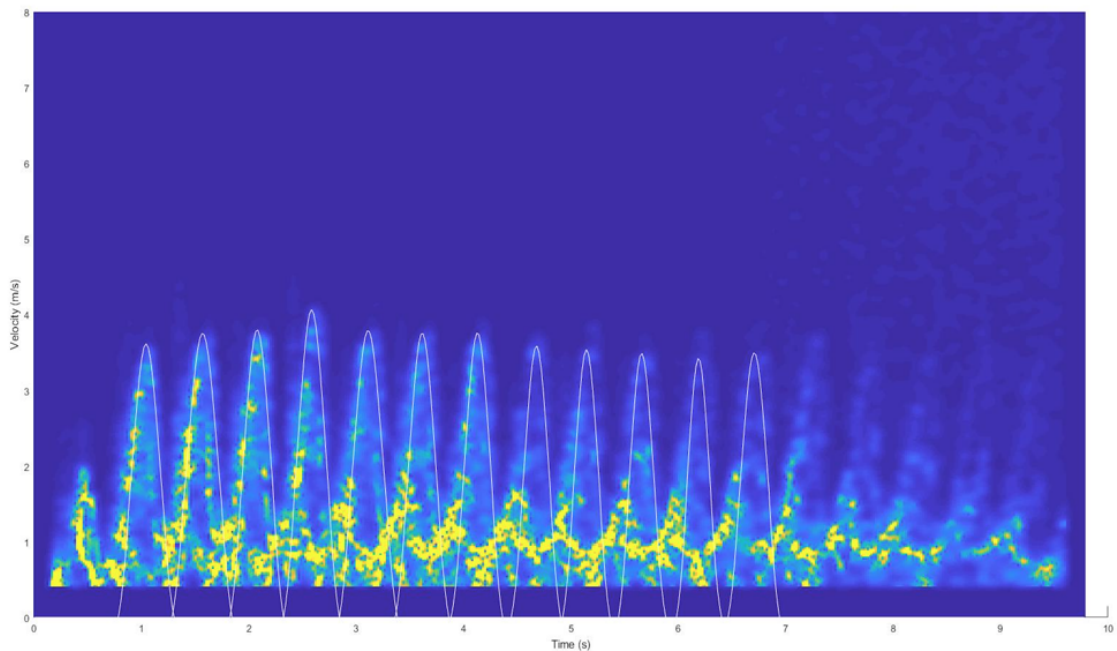


Figure 5.17: Newly Modeled Curve fitted over the spectrogram of normalized walk

```

    peakFootVels: [12x1 double]
meanPeakFootVels: 3.6709
peakFootVelsSTD: 0.1811
    stanceTimes: [0.5600 0.5200 0.5600 0.5600 0.5400 0.6200 0.6000 0.5800 0.6600 0.6200]
meanStanceTimes: 0.5820
    stanceTimesSTD: 0.0426
    swingTimes: [12x1 double]
meanSwingTimes: 0.4483
    swingTimesSTD: 0.0430
    strideTimes: [1.0400 1.0400 1.0200 1.0400 1.0400 1.0800 1.0400 1 1.0600 1.0200]
meanStrideTimes: 1.0380
    strideTimesSTD: 0.0220
meanSwingStanceRatio: 0.7703
    stanceTimePGC: [53.8462 50 54.9020 53.8462 51.9231 57.4074 57.6923 58.0000 62.2642 60.7843]
meanStanceTimePGC: 56.0666
    stanceTimePGCSTD: 3.8591
    stepCadence: 116.6078
    strideDistances: [12x1 double]
meanStrideDistances: 0.9631
    strideDistancesSTD: 0.1309
averageStrideVelocities: [12x1 double]
meanAverageStrideVelocities: 2.1411
averageStrideVelocitiesSTD: 0.1054
    doubleStanceTime: [0.0400 0.0200 0.0400 0.0200 0.0400 0.0800 0.1200 0.0400 0.1000 0.1400 0.1200]
meanDoubleStanceTimes: 0.0691
    SIamp: 2.0318
    SIvels: 1.8603
    swingTimeSI: 2.2305
    gaitSpeed: [0.9710 1.1035 1.0060 1.0884 1.0719 0.9208 0.9183 0.8739 0.7824 0.8015]
meanGaitSpeed: 0.9538
    walkRatio: 121.0755

```

Figure 5.18: Gait Parameters and its values obtained after processing

Chapter 6

Testing Accuracy of Collie Box using Force Plate Sensors

The modeled software processes and presents the gait parameters in numbers as a result. The result of all parameters except the foot peak velocity is dependent on heel-down time and toe-off time. While comparing the result of the Collie Box, the comparison is measured by the difference in heel-down and toe-off time. For measuring the heel-down and toe-off time, the force plate sensor is considered to be ideal. To find the accuracy of the Collie Box, the force plate sensor was synchronized with the Collie Box. For synchronizing, the LabVIEW code which was designed for the data acquisition of signals from Ultrasonic Transducer was updated to fit four more force plate sensors. The addition of four force plate sensors in the data acquisition board allows for synchronous capture of Ultrasonic Doppler and force plate signals of humans in motion. Further, the Matlab image processing code was edited for the easier comparison of the heel-down and toe-off time obtained by Ultrasonic and force plate Sensor.

6.1 Addition of Hardware component (Force plate Sensor)

In our experiment, we added a force plate sensor to check the accuracy of the Collie Box. This force plate sensor “FSR 408” used in the experiment is a series of Force Sensing Resistor family manufactured by Interlink Electronics. In total, four force plate sensor was used in the experiment. Each of these sensors has a length of 622.3mm. The active sensing range of the sensor is 609.22mm in length and 5.08 mm in width and has a thickness of 0.28mm. The sensor’s Force Sensitivity Range can vary from 0.1N to 10.02N along with actuation force of 0.1N [2]. The diagram of FSR 408 sensor can be seen in Figure 6.1.

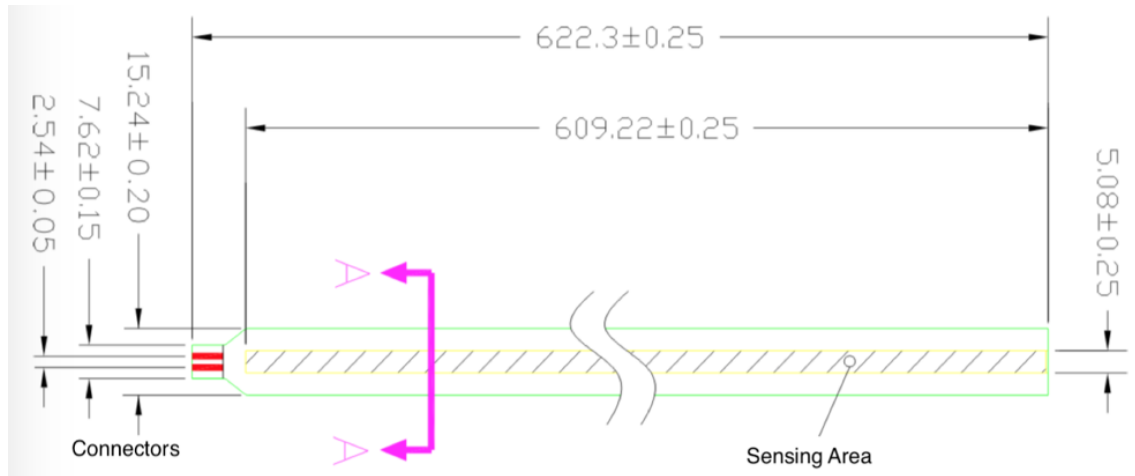


Figure 6.1: Dimension of Force Sensitive Resistor (FSR) 408 Sensor, Source:[2]

6.1.1 Working principle of Force Plate sensor

Force Sensing Resistors or FSR are robust polymer thick film (PTF) devices that exhibit a decrease in resistance with an increase in force applied to the surface of the sensor [20]. The force plate sensor is composed of different layers which are conductor, spacer, FSR layer, and rear adhesive. These layers of FSR sensor are represented in Figure 6.2 and the laboratory version of FSR 408 is shown in Figure 6.3. When the

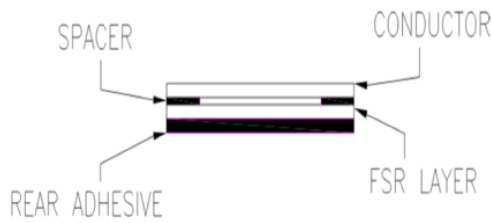


Figure 6.2: Different layers of FSR.
Source:[2]



Figure 6.3: FSR used in Lab

force is applied, the conductor and the FSR layer get in touch as the air from the spacer is pushed through the air vent. The more force applied, the more portion of conductor and the FSR layer get in touch which decreases resistance [21].

6.1.2 Pre-Amp for Force Sensor

The force plate sensor's output was sent to a preamplifier before it was passed to the data acquisition board. The main purpose of the preamplifier circuit designed for the force plate sensor is to provide gain to the output signal. The preamplifier circuit was designed by Professor Murray Korman, US Naval Academy.

The pre-amp circuit has a gain of 16 and offset of 4.27 V. The preamplifier uses an op-amp IC called "LF 356N", manufactured by Texas Instruments. All together four preamplifier were used for amplifying the signals of four force plate sensors. The initial circuit provided by Professor Murray Korman consisted of two amplifiers. Further, two additional preamplifier circuits were built. The preamplifier circuit designed by Professor Murray Korman had two potentiometers in each circuit which was replaced by the two fixed resistors of value $10k\Omega$ in newly built preamplifiers.

6.2 Software Editing

For the comparison of the heel-down and toe-off time of force plate sensor, two software codes needed to be updated. The two software and their updates are described below:

6.2.1 EchoGt_trig.exe(LabVIEW)

Once the force plate sensor was connected with the preamp circuit, the next problem was to acquire the signal data of the sensor using NI Data Acquisition board. The previous code used for the Collie Box was designed in such a way that NI Data Acquisition would acquire input signals from a single channel which was for the ultrasonic transducer. The new modification was needed in the code so that the data acquisition board could acquire input signals from five channels including a channel dedicated to the Ultrasonic Doppler signal. In LabVIEW, the channels were created using “DAQmx Create Virtual Channel” which was linked with “Input Voltage Range”. Then the four additional sensors acquisition follows the same process as the acquisition process of ultrasonic transducer. The interface was redesigned to fit four sensor graph which can be seen in Figure 6.4. The coupling for the incoming Force plate signals is set to DC coupling and the sampling frequency is set to be the same as the sampling frequency of ultrasonic sensor which is 100kHz. The code is updated so that the data acquisition device samples all five input channels at the same time with the same sampling frequency of 100kHz. The obtained output from each force plate sensors and ultrasonic transducer is then saved into a different file having extension of “.d”.



Figure 6.4: EchoGt_trig(LabVIEW) software after 4 Force Sensors were added

6.2.2 EchoGTAnalyzer.exe(Matlab)

The Matlab code was modified to plot the data of four force plate sensor and ultrasonic sensor. At first, the data from the ultrasonic transducer was processed to produce the modeled curve that fits the leg swings. Then the code was updated so that the data from the force plate sensor can be plotted along with the data from ultrasonic transducer. For this, a new Matlab file was created so that it can read data from all four force plate sensor and export all data through a function to the main code. The new Matlab file was named “Force_plate_data.m”. The “Force_plate_data.m” file was called in the main Matlab file which contains the processing code for ultrasonic transducer data. After that, the curve obtained as a result of processing Ultrasonic data was plotted with the force plate sensor’s data in the same figure. This makes it easier to compare the heel-down and toe-off time of ultrasonic transducer and force plate sensor. The representation is shown in Figure 6.5.

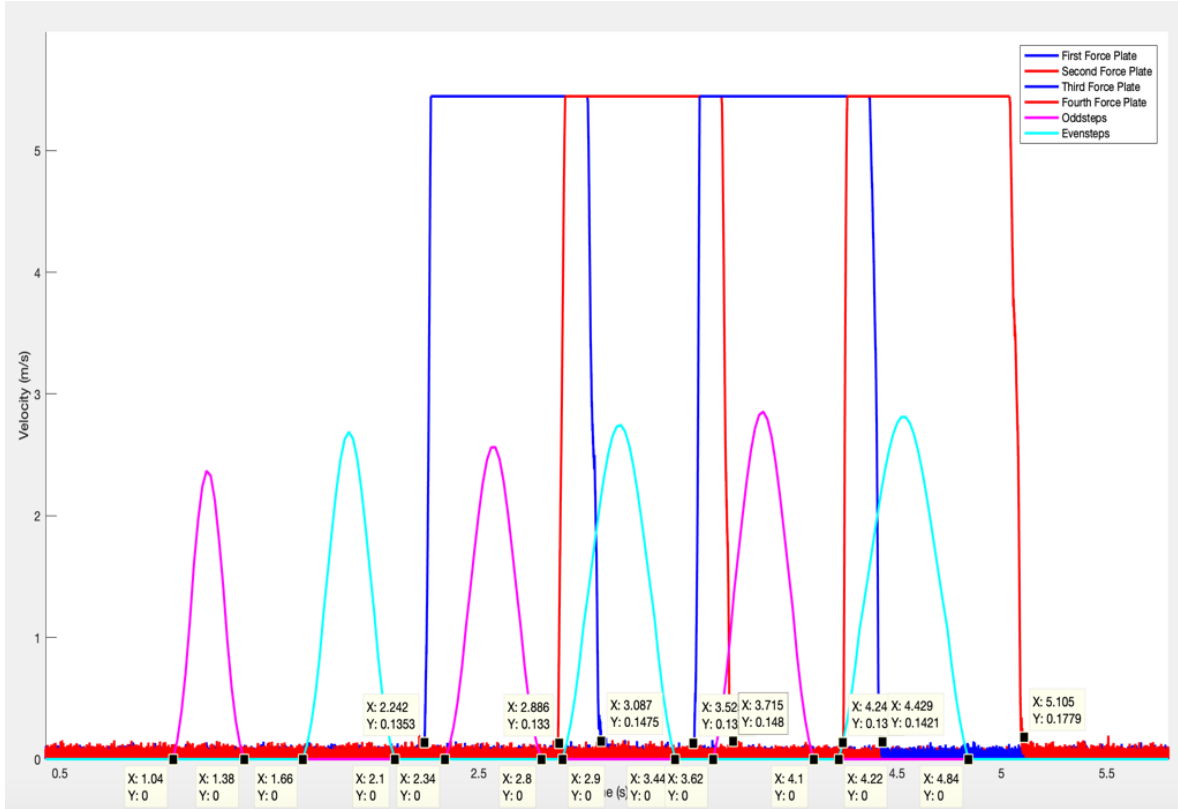


Figure 6.5: Ultrasonic Transducer and Force Plate Sensor data for the same walk

6.3 Procedure of the Experiment

For the process of comparing the results of ultrasonic transducer and force plate sensor, both devices have to be synchronized and should take results from the same walk. The ultrasonic transducer was placed in one corner. The spots where the foot would land while walking were covered with force plate sensors. Both devices were connected to the same data acquisition device and four force plate sensors were used. The ideal setup and laboratory setup are shown in Figure 6.6 and Figure 6.7. When the “EchoGT_trig.exe” software triggers the data acquisition process, the 40kHz signal is transmitted by the Ultrasonic transducer. After that, the normal walk begins. The Doppler shift of walk is captured by Ultrasonic transducer and the force applied by heel-down and toe-off is captured by the force plate sensor. Since both sensors collect

data for the same walk at the same time, the heel down and toe-off time obtained from the modeled curve fit of ultrasonic transducer can be compared with the heel-down and toe-off time from force plate sensor. Measurement was taken for walking in both directions. Both walking away from the transducer and towards the sensor.

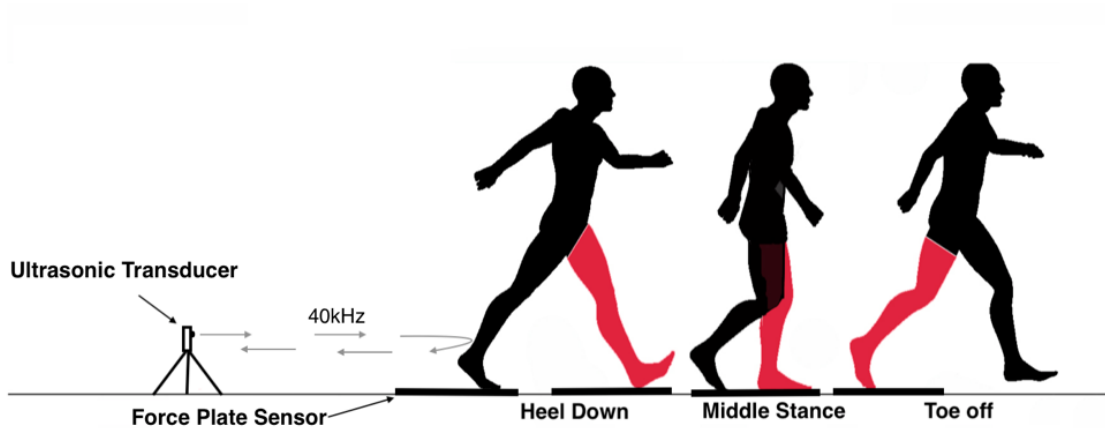


Figure 6.6: Experimental procedure after adding Force Sensor. Source:[1]

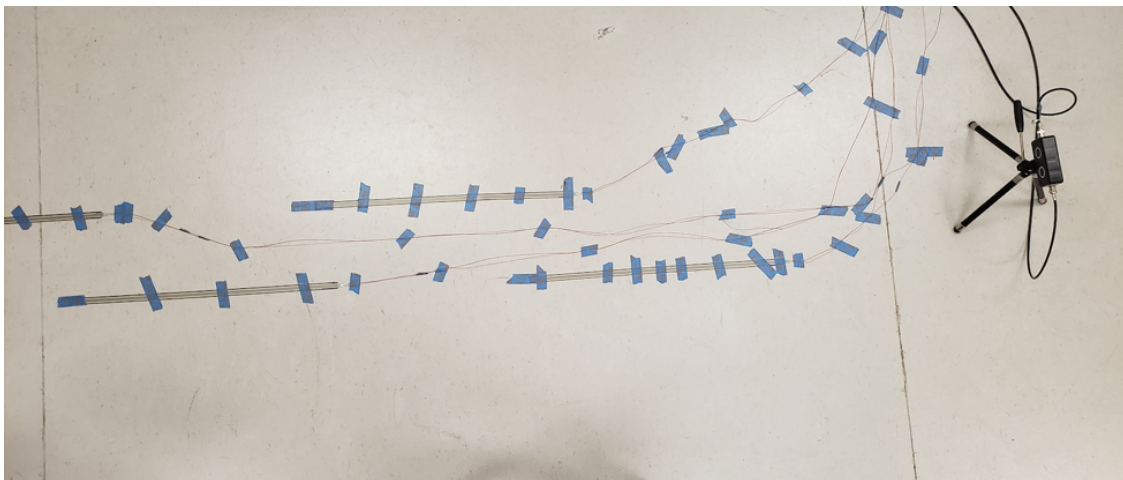


Figure 6.7: Laboratory setting for the experiment

6.4 Results

For comparing the results of force plate sensor and ultrasonic transducer, five sets of data were taken into consideration for measurement dealing with walking away from

the ultrasonic transducer. Also, eight sets of data were taken into consideration for measurement dealing with walking towards the Ultrasonic Transducer. Using those sets of data, the measurement error of Collie Box (the difference of heel-down and toe-off time measured with ultrasonic transducer and force plate sensor) was calculated for both walking towards and away from the ultrasonic transducer.

File	Heel-down(Away)	Heel-down(Towards)	Toe-off(Away)	Toe-off(Towards)
Mean	0.075s	0.102s	0.16s	0.112s
SD(σ)	0.024s	0.042s	0.026s	0.034s

Table 6.1: Comparison of difference of Heel down and toe-off Time

The expression mentioned in Table 6.1 are explained below:

- **Heel-down(Away)**

| Heel-down time measured by (Force Plate Sensor - Ultrasonic Transducers) |
 (Note: While walking Away from ultrasonic transducer)

- **Heel-down(Towards)**

| Heel-down time measured by (Force Plate Sensor - Ultrasonic Transducers) |
 (Note: While walking Towards Ultrasonic transducer)

- **Toe-off(Away)**

| Toe-off time measured by (Force Plate Sensor - Ultrasonic Transducers) |
 (Note: While walking Away from Ultrasonic Transducer)

- **Toe-off(Towards)**

| Toe-off time measured by (Force Plate Sensor - Ultrasonic Transducers) |
 (Note: While walking Towards Ultrasonic Transducer)

The first observation from Table 6.1 is that the difference of heel-down time was smaller than the difference of toe-off time while walking in both directions. This means that the Collie Box can detect heel-down better than the toe-off. The second

observation is that the difference of heel-down time is smaller while walking away from the sensor but the difference of toe-off time is smaller while walking towards the sensor. This indicates that Collie Box detects heel down better while walking away from the sensor. Also, it explains that the Collie Box detects toe-off better while walking towards the sensor.

Chapter 7

Improving accuracy of Collie Box

Collie Box isn't perfectly accurate. The main cause of the inaccuracy in Collie Box is the wide directivity of single 10mm ultrasonic transmitter. The wide directivity resulted in the Doppler shift from not only the foot but also from the torso of the human body. In a normal walk, the torso part of the human body is always in motion whereas the foot comes to complete rest at each step. The torso in motion has a comparatively lower velocity than of the foot. Due to this reason, the heel-down and toe-off time is overlapped by the velocity of torso in motion and cannot be detected. Hence, the curve fitting is used which determines the nature of the curve and tries to fit function in each leg swing so that it can predict the heel-down and toe-off times.

The main goal is to obtain the Doppler shift from foot only. This helps the device to get actual heel-down and toe-off times. The wide directivity of the single 10mm ultrasonic transducer comes with bigger inaccuracy while carrying out this process.

7.1 Directivity of Transducers with different sizes and arrangement

To extract Doppler shift from the foot, the transducer's directivity needs to be very narrow. To find the narrow directivity transducer, ultrasonic transducer with different sizes and arrangement are compared.

7.1.1 Single transducer of 10mm

Microphone and angular rotator was used for finding the directivity of single 10mm ultrasonic transducer. Also, the foam was used on both sides to absorb the reflection. While calculating the directivity, the following things were taken into consideration:

Angle of Rotation of Transducer:	From 300° to 60° (Total 120° rotation)
Angle of Rotation per step:	2°
Voltage supplied:	10V _{pp}
Frequency Supplied:	40KHz
Distance between Transducer and mic:	1m
Height of transducer and Mic:	18cm

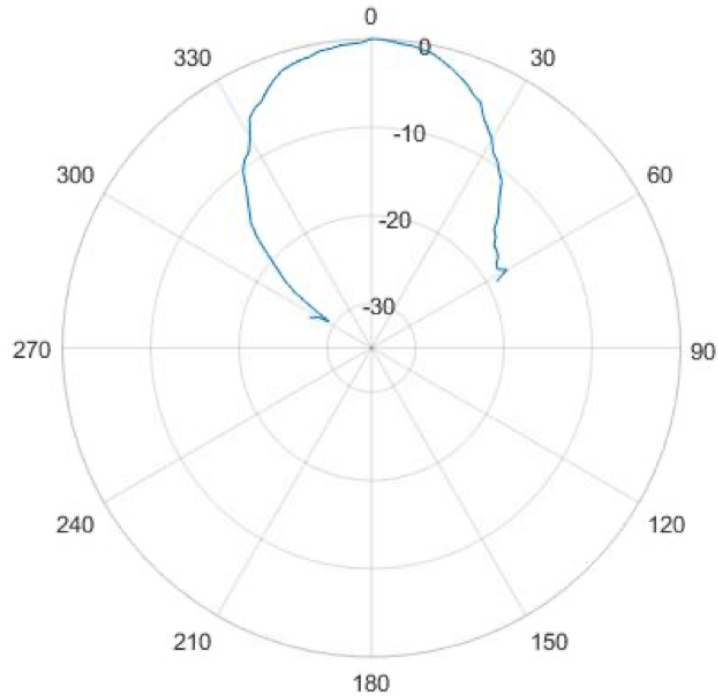


Figure 7.1: Directivity of Single 10mm transducer

Observing Figure 7.1, we confirmed that Single 10mm ultrasonic transducer has wide directivity.

7.1.2 Linear Array (10 transducers of 10mm)

Our next step was to test a phased array of ultrasonic transducer. For this, 10 transmitters were used in a linear array form. Glass frame to fit ten transducers was made. All transmitters were fitted in the frame and the transmitted signal was received using a microphone. The experimental setup of those transducers can be seen in Figure 7.2.

Also, the following things were taken into consideration while measuring the directivity of phased array of 10mm transducer:

Angle of Rotation of Transducer:	From 270° to 90° (Total 180° rotation)
Angle of Rotation per step:	2°
Number of Transducers used:	10
Voltage supplied:	$10V_{pp}$
Frequency Supplied:	40KHz
Distance between Transducer and mic:	0.6m
Height of transducer and Mic:	18cm

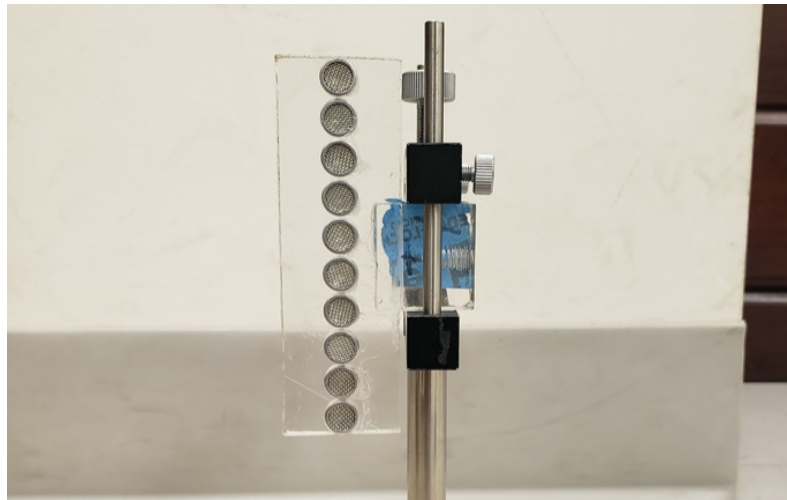


Figure 7.2: Experimental setup of Linear array of 10 transducers of 10mm

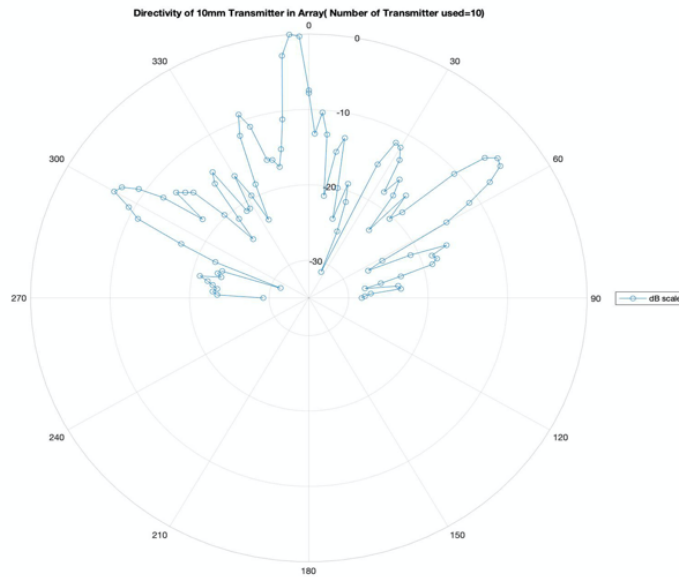


Figure 7.3: Directivity of array of 10 transducers of 10mm

In Figure 7.3, it showed that the directivity of the phased array of transducers is narrower than the directivity of the single transducer. In the polar plot graph, there are 5 major lobes. The two lobes at 300 degrees and 55 degrees have higher decibel which shows that the phased array of transducer still gets Doppler shift data from wide-angle at high intensity. This shows that the phased array of 10mm transducer is not still able to decrease the inaccuracy of Collie Box by a huge margin.

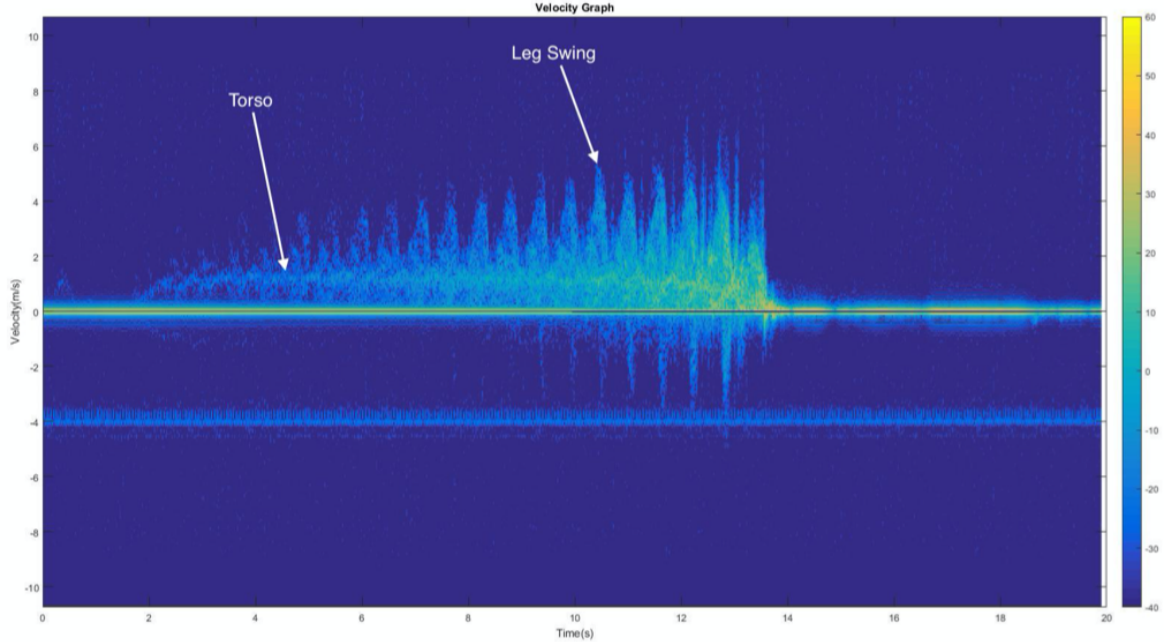


Figure 7.4: Unprocessed Spectrogram of beamed 10mm Transducer

To test the application of phased array of 10mm transducer, the unprocessed spectrogram of human walking towards the transducer is plotted. In Figure 7.4, the torso part of the human body can be seen along with the leg swing where the torso has low velocity and leg swing has high velocity. In the above graph, the heel-down and toe-off times cannot be seen. This shows that the Collie Box still gets more Doppler shift signals from the torso part of humans.

7.1.3 Linear Array (10 transducers of 3.7mm)

The next arrangement to test is the phased array of 3.7mm ultrasonic transducer. The 3.7mm transducer was made using shrinking tube. The one end of the shrink tube has an opening of 3.7mm and the other end is connected to 10mm transducer. The total length of the tube was modeled to be 67.1mm. These transducers arranged in the air-coupled phase array form can operate at 40kHz without any grating lobes [22]. The rest of the 10 transducers of 3.7mm were made using the same technique and fitted in the glass frame. The setup of the transducers can be seen in Figure 7.5.

The following things were taken into consideration while measuring the directivity of 10 transducers of 3.7mm.

Angle of Rotation of Transducer: From 270° to 90° (Total 180° rotation)

Angle of Rotation per step: 2°

Number of Transducers used: 10

Voltage supplied: $10V_{pp}$

Frequency Supplied: 40KHz

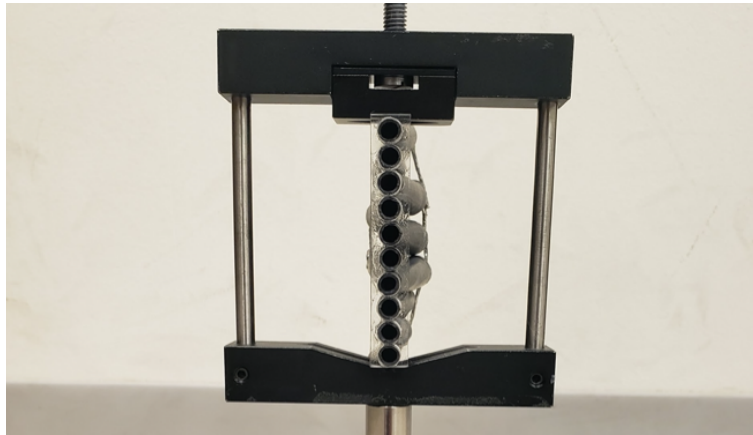


Figure 7.5: Experimental setup of Linear array of 10 transducers of 3.7mm

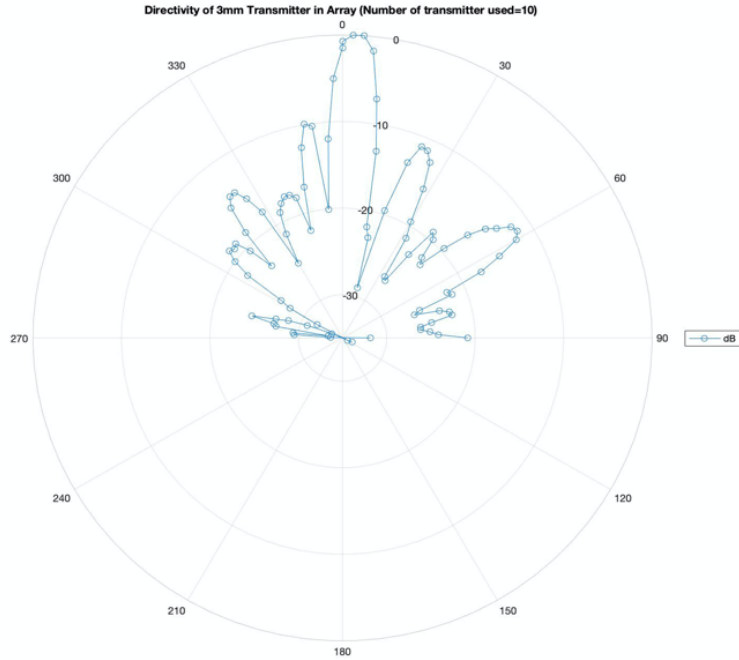


Figure 7.6: Directivity of array of 10 transducers of 3.7mm

The directivity of the phased array of 3.7mm transducer is narrower than both single and phased array of 10mm transducer. In Figure 7.6, it shows that the directivity of phased array has one major lobe and several other smaller lobes. This shows that this arrangement has better and narrower directivity. Same arrangement of phased array of 3.7mm transducer was picked on further experiments in testing the difference in heel-down and toe-off time between ultrasonic transducer and force sensor.

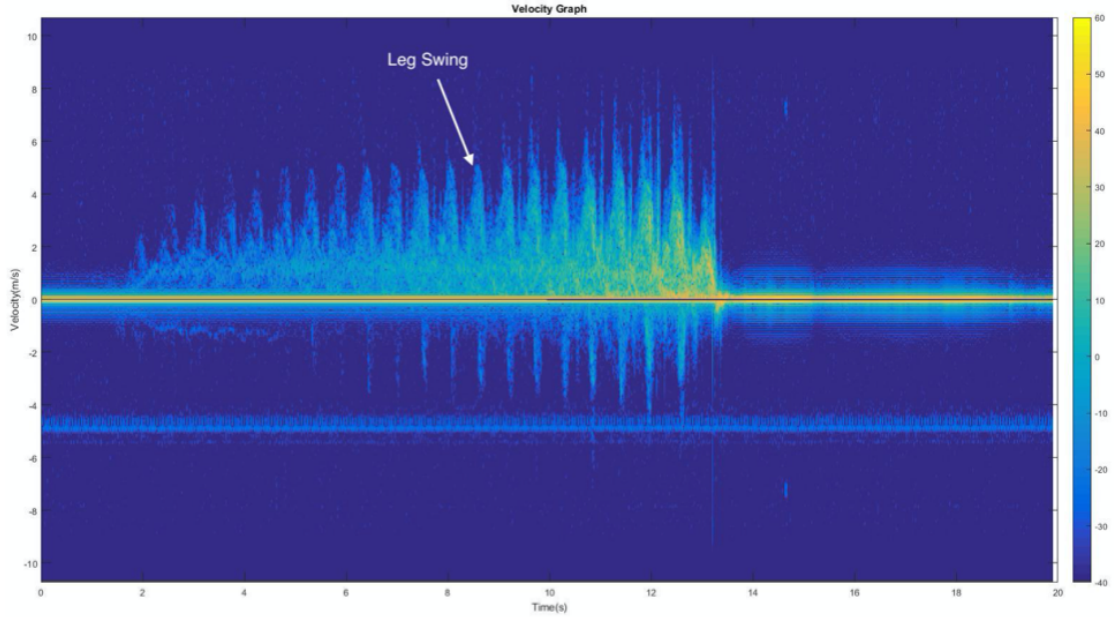


Figure 7.7: Unprocessed Spectrogram of beamed 3.7mm Transducer

To further test the application of the transducer arrangement, the Doppler shift of humans in motion was recorded. The walk was made in front of the phased array of 3.7mm transducer. The unprocessed spectrogram of the walk was plotted using Matlab. In Figure 7.7, it can be seen that the Doppler shift signal from the torso obtained using phased array of 3.7mm transducer was less when compared with the unprocessed spectrogram of phased array of 10mm transducer.

The accuracy of each arrangement of transducers is verified with the help of the force plate sensor. The process of comparing the heel-down and toe-off time between force plate sensor and phased array of 3.7mm transducer is similar to the previous process for comparing of single 10mm transducer. Data for walking in both directions, towards and away from the Collie Box were taken into consideration while comparing the heel-down and toe-off time.

7.2 Results

7.2.1 Comparison of Unprocessed Spectrogram

While comparing unprocessed spectrogram, the phased array of 3.7mm transducer seemed to receive less Doppler shift signals from the torso when compared with the spectrogram of the phased array of 10mm transducer. The unprocessed spectrogram of the phased array of 3.7mm transducer also shows that the transducer received more signal from the foot. This agrees with the directivity results of phased array of 3.7mm transducer.

Walking Away				
File	Heel-down(Single)	Heel-down(Array)	Toe-off(Single)	Toe-off(Array)
Mean	0.075s	0.117s	0.16s	0.179s
SD(σ)	0.024s	0.067s	0.026s	0.058s

Table 7.1: Comparison of single and linear array of 3.7mm transducer

The expression mentioned in Table 7.1 are explained below:

- **Heel-down(Single)**

| Heel-down time measured by (Force Plate Sensor - Ultrasonic Transducers) |

(Note: Single ultrasonic transducer is used)

- **Heel-down(Array)**

| Heel-down time measured by (Force Plate Sensor - Ultrasonic Transducers) |

(Note: Linear Array of 3.7mm ultrasonic transducer is used)

- **Toe-off(Single)**

| Toe-off time measured by (Force Plate Sensor - Ultrasonic Transducers) |

(Note: Single ultrasonic transducer is used)

- **Toe-off(Array)**

| Toe-off time measured by (Force Plate Sensor - Ultrasonic Transducers) |

(Note: Linear Array of 3.7mm ultrasonic transducer is used)

From Table 7.1, we can conclude that the average error of heel-down and toe-off time is smaller with the single 10mm transducer while compared with the phased array of 3.7mm transducer. This indicates that the Collie Box using a single 10mm transducer performed better than the phased array of 3.7mm transducer.

Chapter 8

Conclusion

We found that the Collie Box performed better at detecting heel-down time while walking away from the transducer. The Collie Box also performed better at detecting the toe-off while walking towards the transducer. This shows that the percentage error of the Collie Box varies while walking towards or away from the transducer.

Also, when the result of Collie Box was compared with the force plate sensor, we realized that the Collie Box detected both heel-down and toe-off before the event occurred. The main cause of the error is the wide directivity of the single 10mm transducer which is used on the Collie Box. To reduce the error, we tried comparing the result of a single 10mm transducer with the phased array of 3.7mm transducer which has narrow directivity.

While comparing the spectrogram of raw data of single 10mm transducer with the phased array of 3.7mm transducer, the phased array of 3.7mm transducer performed better. Due to the narrow directivity of the phased array of 3.7 mm transducer, it captured more data from the foot and fewer data from the torso while a single 10mm transducer captured comparatively more data from the torso.

While comparing the average of heel-down and toe-off time error of the processed data, we noticed that error measured using a single transducer was smaller while

compared with the error measured using phased array of 3.7mm transducer. This shows that the single transducer performed better after processing. The main reason for this unexpected outcome is that the data analyzing software is only optimized for the single transducer but not for the phased array transducer. There are many constants in the data analyzing software's code which was calculated only for a single transducer.

In the near future, we are working to optimize the software for the phased array of 3.7mm transducer. Once the software is optimized, the same experiment will be repeated.

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