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Development of a non-invasive screening technique for detection of wrist fractures in children

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Abstract. A study applying vibration analysis was conducted on the wrists of children aged between 10 and 15 years old to determine the presence or absence of fracture, following wrist trauma. Without radiographs it is not possible for a doctor to confirm whether trauma has resulted in a sprain or a fracture. The current waiting time for patients to see a doctor is set at 4 hours by the National Health Service of the U.K. This means that many children (who only have a sprain) are exposed to unnecessary radiation and they and their guardians are spending needless hours in the Emergency Department and potentially prolonging the stay of others. Therefore, a screening tool is required to more precisely select those children who should proceed to radiographic examinations. We have developed a hand-held vibration inducer that sends vibrating signals through the long bones for a small period of time. This device is pre-programmed and captures the corresponding vibration responses by means of a piezoelectric sensor. Data were recorded from the local children's hospital. Noise and distortion of the signals were removed as much as possible by three methods. The methods consist of subtraction of the root mean squared signals from each signal acquired, filtering the resulting signals and finally application of a suitable windowing method. The frequencies were classified by the 'Maximum Likelihood Estimate'. The frequencies were separated into two groups: males and females for clearer comparisons. All analyses were compared with x-ray findings.

Keywords: Vibration, Frequencies, Signals, Screening, Maximum Likelihood Estimate

1 Introduction

A fracture is a break in a bone usually occurring when there is an impact or force applied to it. The natural reflexive movement for any person falling is to extend their hand to reduce the impact of the fall which may cause an upper limb (usually a wrist) fracture. Fractures constitute around one-fourth of all pediatric injuries [1]. Studies conducted by [2] suggested that boys sustain more childhood fractures than girls and 30% of fractures in both sexes occur in the radius/ulna (long bones of the forearm). 30% patients with significant soft tissue injuries, such as, sprains, strains, etc. do not get correct diagnosis [3].

When a child injures his/her wrist, s/he attends the Emergency Department along with their guardians to see a doctor. Doctors cannot confirm the status of an injury as a fracture or a sprain, until the patient has an x-ray. If the child has a sprain, then they may wait for about 4-hours and be exposed to unnecessary radiation. Thus, a non-invasive technique has been developed as a screening method to reduce the problems noted above. Vibration analysis has been studied as the potential method.

A screening test is not to be confused with a diagnostic test because it is a test performed to confirm if a patient needs to have the diagnostic test. According to [4-5], screening tests are widely used in medicine as a first step to decide if more appropriate assessments are required to detect an abnormality or disease.

Vibration analysis is a widespread and reliable technique used in industry that allows diagnostics, fault detection and condition monitoring of machines [6]. The vibration calculation consists of processing vibration signals' frequencies that can specify the location of the problem and its type [7]. Due to the success rates in industrial applications, vibration analysis is gaining popularity in medical fields. It is being examined as a likely technique for fracture healing [8-9], and the prevention of osteoporosis [10-12]. This is due to the fact that vibrational analysis in industrial applications can help determining cracks in materials, and hence it may help to determine fractures in bones, which is the aim of this study.

Vibration analysis can be grouped into four main domains [13]: Time domain, Frequency domain, Joint (time &/or frequency) domain and Modal analysis. In other words, when signals are produced by vibration of a body, they can be analyzed in respect to time or by converting them to frequency spectra or by combining both time and frequency.

There are two kinds of stimuli that can be applied to the human skeletal system to induce vibration [14]:

- Impulse Vibration Excitation and
- Continuous Vibration Excitation.

Impulses may be generated using tapping (e.g. a light instrumented hammer or pendulum devices). The excitations are usually periodic in nature. Oscillations are generated as a result of platform switching procedures and external transients like electromagnetic pulses or lightning [15]. This research utilized this technique.

2 Methodology

50 children with wrist injuries participated in this study. They all came to the Emergency Department of a local hospital with the injuries and all of them had x-rays on the basis of clinical need. Following the full informed consent from 50 children and assent from their parents/legal guardians, data have been captured from them.

2.1 Hardware

In this study, a suitable hand-held and portable vibration inducing and recording device has been developed. The following list of equipment has been used.

- A hand-held steel covered vibration inducer to induce oscillating signals. It has been held gently on the most prominent bone in elbow for 10s (seconds) to create 10 impacts.
- A highly sensitive piezoelectric sensor has been placed for 10s on the skin above ulna to capture the vibration responses because the excitation procedure occurs for a very short period of time, a highly sensitive sensor with a buffered output has been used to pick-up the response. For this study, the sensor has been enclosed by a plastic body to cover the outer body of the sensor, in order to ensure patients' safety.

- An interfacing board has been used to convert the digital signal produced by the computer required to the analogue state for controlling the excitation system. This conversion process was achieved by using a National Instrument (NI) myDAQ[1]. It is a portable data acquisition system to carry out analogue-to-digital conversion and vice versa.
- The entire device has been powered by a portable battery of 12V.
- A suitable Printed Circuit Board (PCB) has been designed to filter and amplify the resultant responses and a power divider has also been included to feed the appropriate level of power to run each component.

2.2 Software

Two programs have been designed to run in parallel. One program can send commands to run the inducer for the time set and another program controls the sensor to make it capture the data and saves the data to the computer connected.

Three factors that were very important while designing:

- The 'Duty Cycle' of the sending signal had been 5% only (kept small to cause no discomfort to the patients).
- A 'Delay' has been applied, so that before instructing the inducer to 'run', time is allowed to hold the sensor on the target appropriately. In practice, after pressing 'Start', the vibration mechanism waits for 7s before it starts running and data are not recorded at that time.
- Number of Impacts' has been set to 10 so that the vibration mechanism hit the target in front of it, 10 times in 10 seconds. This was determined by experiment in order to balance between enough data for analyses and not too much to keep patients comfortable.

3 Results

3.1 Initial Analysis

Various techniques had been applied to process the data to find out the most appropriate one that can process the data correctly as much as possible. Figure 1 is a representation of a raw signal.

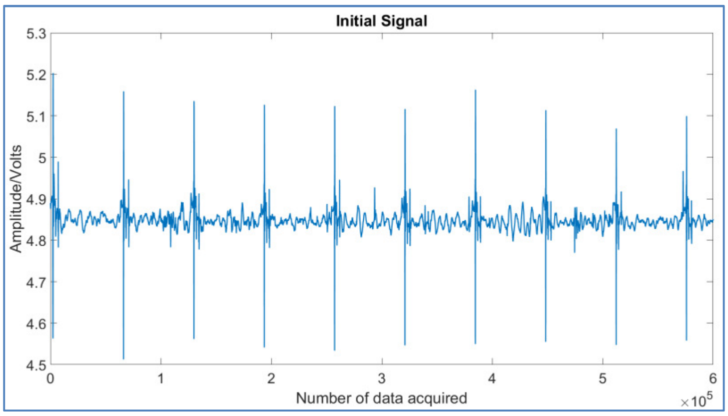

Fig. 1. Vibration response captured by the sensor.

[1] http://www.ni.com/en-gb.html

In order to maintain the consistency of the data, the mean of the total data were subtracted from each dataset. The resultant signals were initially filtered with a low pass Butterworth filter with the following specifications:

- order = 5 (a standard value),
- cut-off frequency = 2000 Hz,
- sampling frequency of the filter = 50,000 samples/s.

The filtered signal had been processed via fast Fourier transform (FFT) to generate the frequency spectra, shown in Figure 2.

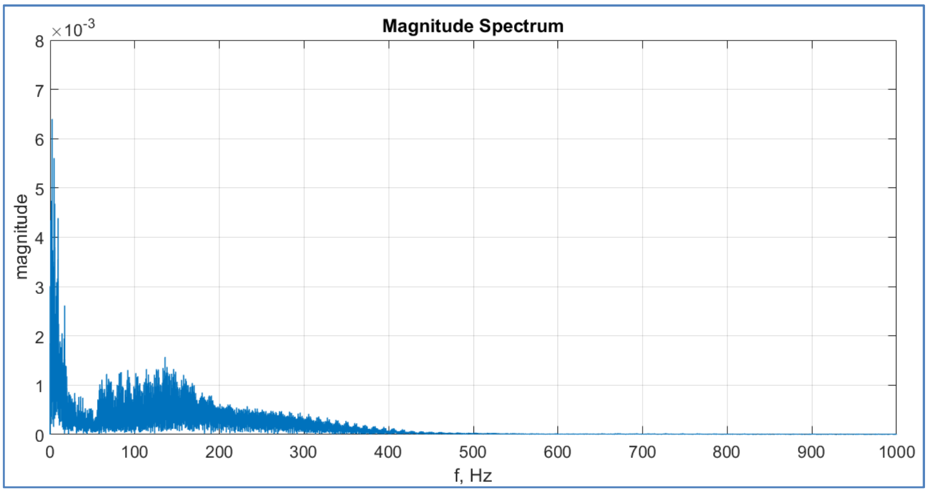

Fig. 2. Magnitude Spectrum over a range of 1000Hz.

Initially the widely known clustering technique 'Fuzzy C-means (FCM)' had been selected to treat the frequency spectra.

Table 1. Initial comparisons of Vibration analyses' results with x-rays.

Participant Number	**Results by x-ray**	**Results by Fuzzy C-Means (with membership values/likelihood of being fractured)**
1	No fracture	Fracture (0.8969)
2	No fracture	Fracture (0.9111)
3	Fracture	Fracture (0.9529)
4	No fracture	No fracture (0.2121)
5	No fracture	No fracture (0.1664)
6	No fracture	No fracture (0.1906)
7	No fracture	No fracture (0.2159)
8	Fracture	Fracture (0.8415)
9	No fracture	Fracture (0.9606)
10	Fracture	No fracture (0.3036)
11	Fracture	Fracture (0.7551)
12	Fracture	Fracture (0.9923)
13	No fracture	No fracture (0.2887)
14	Fracture	Fracture (0.9749)

The results from Table 1 show that 1 out of 14 patients would leave the hospital without being diagnosed accurately while saving 5 out of 14 patients from unnecessary radiation exposure. The low sensitivity (83%) and specificity (63%) caused us to try other processing methods. Moreover, a very small range of frequency, starting from 20Hz to 500Hz was considered for feeding into FCM analysis, so the processing methods were changed. Simultaneously, more patients were recruited to participate in this study for further comparisons.

3.2 Data Removal and Frequency Analysis

- After collecting 50 sets of data, to improve the filtering of signals, an Infinite Impulse Response (IIR) filter had been designed assigning the order '5', a Passband frequency of 5000Hz and a sampling rate of 60,00samples/second. A suitable window had been applied as well. Windowing method had been developed to remove the undesirable phenomenon such as an overshoot occurring at simple discontinuities sometimes known as Gibbs oscillations that are typically found in the signals processed by IIR filters. About 8000 of the data from each of the taps were removed to observe if there were any effects of introducing the vibrations.

- The magnitude spectra of the new set of data were composed and the mean frequencies were mined from the spectra. These frequencies were presented via a scatter diagram. A cut-off line had been drawn to separate the 'fractured' and 'sprained' frequencies.

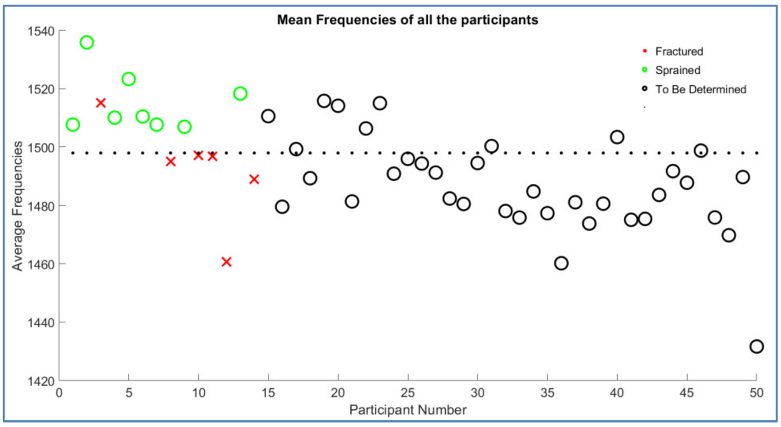

Fig. 3. Mean Frequencies of all the participants with 'green circles' for sprain, 'red cross' for fracture and 'black circles' remaining to compare with x-ray for confirmation.

As shown in Figure 3, the black circles represented the 36 new recruitments, and these were matched with x-ray images. Almost *50%* of the results were *incorrect* when matched with the x-ray reports.

3.3 Cross-correlation

- The frequencies from both the injured and the uninjured wrists were cross-correlated, shown in the 'Results section'. The 'cross-correlation' of two discrete signals measures the similarity.

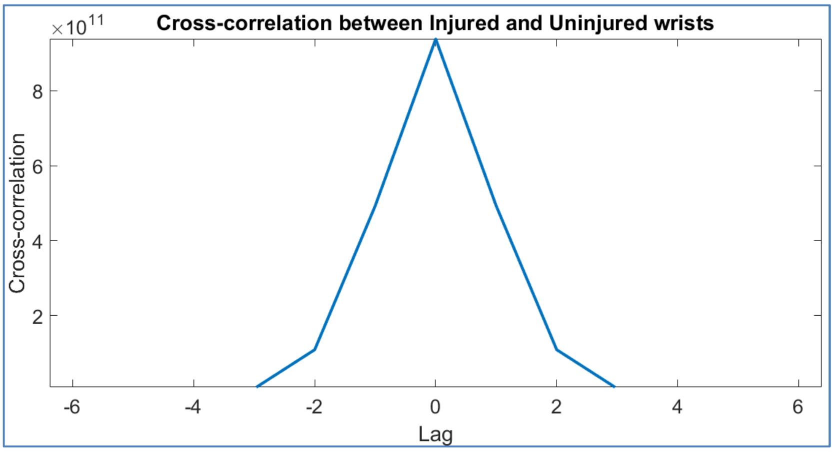

Fig. 4. Cross-correlated values.

- The 'maximum' value was scattered again in the assumption that there would be difference in the values and according to existing theories the fractured wrists' data should have lower values than that of the sprained ones. But there was no pattern.

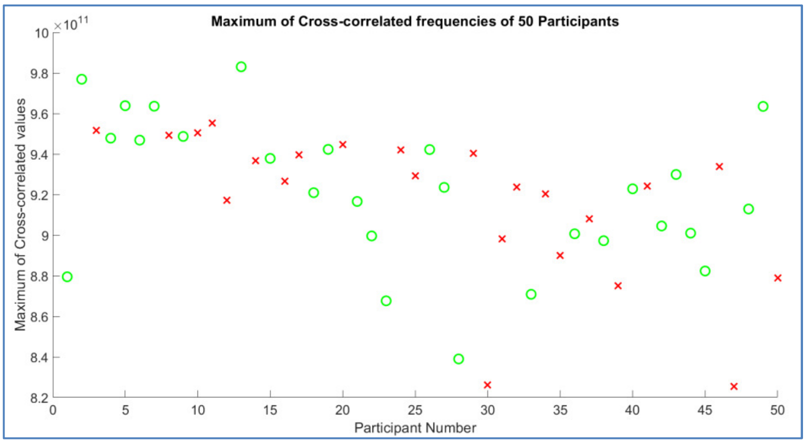

Fig. 5. Maximum Cross-Correlated values between injured and uninjured wrists with fractured (red-cross) and sprained wrists (green-circles).

- In this study, only features like fracture and sprain were considered so far. But the difference in sexes might have some effects on the recordings. [16-17] have demonstrated that there is an effect of the sex of a person on the bone strength and bone density. Studies conducted by [18] indicate that there is a direct relation between the changes of bone density and bone natural frequency. Thus, the data have been re-scattered separating the male and female participants. Fractured and sprained data did not get separated from each other as expected, so some more amendments were made to observe if any difference occurs.

There are very *slight* differences between the values of cross-correlations in average. In average, the maximum of cross-correlated frequencies for:

male participants (fractured) = 9.1010e+11

male participants (unfractured) = 9.2311e+11

female participants (fractured) = 9.2945e+11

female participants (unfractured) = 9.2019e+11

However, the differences warrant for more explorations.

3.4 Frequency Analysis and Maximum Likelihood Estimate

- Frequency analysis was done processing the data more and separating on the basis of sex. New data generated, x = Raw data – rms (Raw data) ('rms' is the root mean square. It expresses the energy of a signal and describes a type of average signal value [19]. An Infinite Impulse Response type filter had been designed by assigning order of 16 and applied to 'x'. The entire length of 'x' was processed via a Hamming window. 400 values (=0.067%) of the data from the frequency spectra were left to minimize the spectral leakage. Filters have been designed starting with order '5' up to '20' to test the effects of filtration of signals on the frequencies. Filter with order '16' generated drew the best separation between the fractured and non-fractured data.

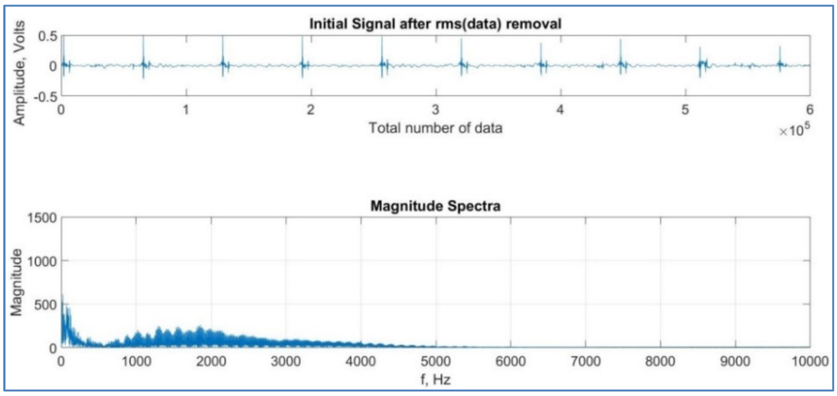

Fig. 6. Newly processed Vibration Response and its Frequency Spectra.

- From the Figure with the new Magnitude spectra, there are no high magnitude frequencies after 4000 Hz so up to 4000 Hz has been included in the amendment. Median (middle) frequencies have been considered due to the presence of various peak frequencies and these have been scattered, however, this time, with male and female participants are drawn in separate diagrams. A cut-off line has been drawn to separate the sprained and fractured data.

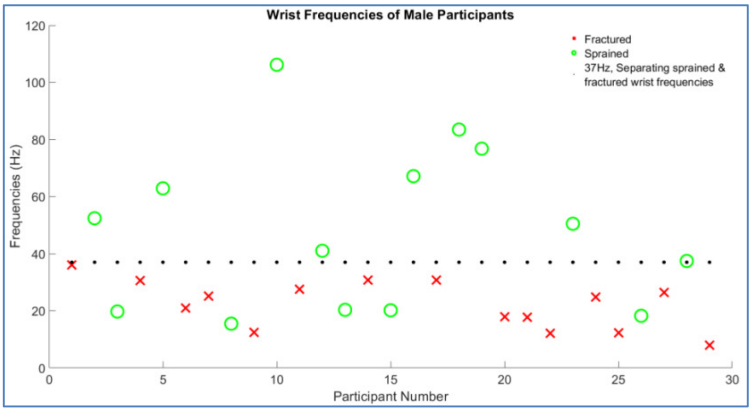

Fig. 7. Median frequencies of Male Patients' Wrists.

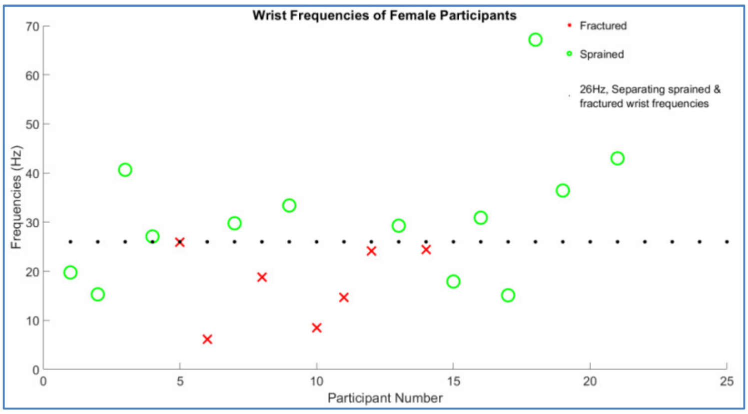

Fig. 8. Median frequencies of Female Patients' Wrists.

- According to Figures 7 and 8, 9 males and 9 females would have been spared from x-ray. Filters have been designed starting with order ‘5’ up to ‘20’ to test the noise removal of signals on the frequencies. Filter with order ‘16’ produced the best separation between the fractured and sprained data. The same methods have been carried leaving 300, 350, 450 and 500 data to investigate if the spectral leakage can be reduced. However, removal of these data does not produce better separation.

- The mean frequencies for males: fractured = 22.24Hz and sprained = 49.29Hz. The mean frequencies for females: fractured = 22.57Hz and sprained = 31.21Hz. Although the mean frequencies for both males and females are nearly the same but the sprained female wrist frequencies are less than that of the males. The fractured wrists may create a distortion when picking up the signals, so the frequencies are likely to fall from the normal range at any rate.

- The command 'Maximum likelihood estimate' (which is referred as the MLE) is the function that can produce the likelihoods based on the occurrence of something happening maximum number of times and also on the confidence levels. It is the procedure of determining the value of one or more parameters for a given statistic that makes the likelihood distribution a maximum.

Table 2. MLE of median frequencies with 90% confidence level.

Category	Maximum Likelihood of Frequencies/Hz
Fractured male patients' wrists	*20.2 to 24.2*
Sprained male patients' wrists	44.9 to 52.4
Uninjured male patients' wrists	37.9 to 41.7
Fractured female patients' wrists	*19.8 to 25.3*
Sprained female patients' wrists	28.7 to 33.8
Uninjured female patients' wrists	40.4 to 45.1

- From Table 2, both male and female participants' MLE of frequencies display that the frequencies of fractured wrists are lower than that of the sprained and normal wrists. The distinguishing boundaries for fractured and sprained wrists are: 24.2 to 44.9 Hz for males and 25.3 to 28.7 Hz for females. The research conducted by [20] on human hand-arm and vibration transmission experiments done by [21] indicate similar outcomes of frequencies.

- *Sensitivity* is the probability that will indicate 'fracture' among those with a fracture. *Specificity* is the fraction of those without fracture that will have a negative test result.

- For the clinicians, the 'Positive Predictive Values (PPV)' and 'Negative Predictive Values (NPV)' are significant. PPV indicates the probability of a disease in a patient when the test result is positive. NPV indicates the probability of the absence of the disease in a person who has a negative test result.

Table 3. Fracture/Sprain Accuracy Measurements for Males and Females.

	Male (%)	Female (%)
Sensitivity	100	87.5
Specificity	64.29	69.23
Positive Predictive Value (PPV)	75	63.64
Negative Predictive Value (NPV)	100	90
Accuracy	82.76	76.19

Interpretation of Table 3 is as follows.

- Sensitivity is 100% (for males) and 87.5% (for females), so the test developed by frequency analysis should be able to detect all the males with fracture and 87.5% of the females with fracture. However, the test misses 12.5% of the females who have fracture. Specificity is 64.29% (for males) and 69.23% (for females).

- The screening test has accuracy of 82.76% with males and accuracy of 76.19% with females.

- This study checked the comfort level of the vibration method with the patients. 26% of the patients said they preferred vibration, 26% said x-ray and 48% said they do not have any preference.

3.5 Probability Plot

- The male and female participants' frequencies had been normally distributed with 95% confidence level. 'Probability plot' had been selected as the display type. The best-fitted line which appears with the frequencies of each case (fractured, sprained and uninjured) had been indicated.

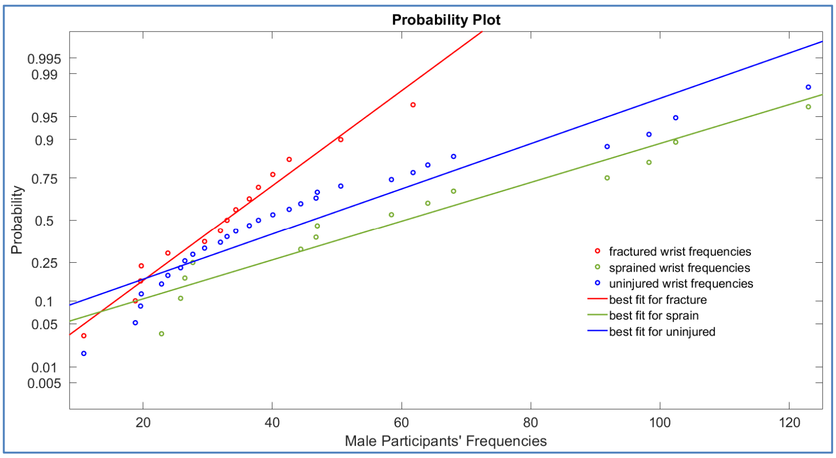

Fig. 9. Frequencies of male participants normally distributed.

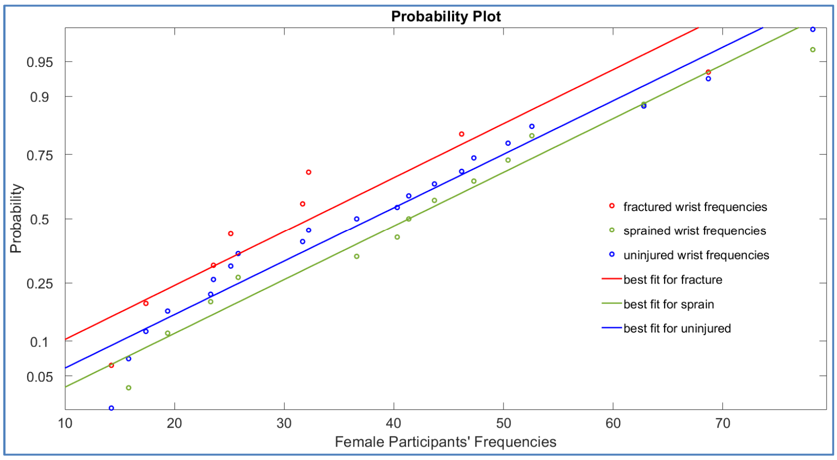

Fig. 10. Frequencies of female participants normally distributed.

It can be seen from both Figures 9 and 10 that there is a clear difference between the frequencies although there are some overlaps. However, 'sprained' data have moved closer to the normal ones. From the pattern, it can be predicted that if more data can be fed then the lines will separate from each other. In that case, if new data are pushed to the *Probability Plot*, the data will locate themselves close to the suitable type of line (red, green or blue).

4 Conclusion

Each x-ray costs around £60. The patients must wait for the doctors to see them (up to 4 to 6 hours) following an injury. Without radiographs, it is impossible for the doctors to determine if an injury is a sprain or a fracture and 60% of the x-rays show there is no fracture, instead it is a sprain. Although extremity x-ray does not expose the patient to much ionizing radiation, it is better if radiation can be avoided.

This research was conducted to see if non-invasive vibration analysis method can be used for differentiating wrist fracture from sprain. Currently, by 'frequency analysis', the accuracy of the technique was ≥ 75+%; it is possible that this can be improved with further modifications to the analysis techniques and increased patient numbers.

The study revealed some properties, for example, the sex of the participants might have impacts on frequencies when screening wrist injuries. But there are other factors which need to be explored as well, for example, age, dominant hands, distance between the site of vibration and the site of fracture, of the participants, etc. A higher number of participants can provide a more solid basis and therefore, a more reliable data set for analysis can be established for the future. Some other signal processing and differentiating techniques can be considered in the further analysis to increase the efficiency of the screening method. Vibration analysis holds promise to be a reliable screening tool to identify children (and adults) who require wrist or ankle radiographs following trauma.

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