EVALUATION AND IMPROVEMENT OF NON-BONDED PIEZO SENSOR (NBPS) FOR BIO-MEDICAL STRUCTURAL HEALTH MONITORING (BSHM)

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(2018CES2182)

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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Submitted by

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In fulfilment of the requirement of the degree of

Master of Technology in Structural Engineering

DEPARTMENT OF CIVIL ENGINEERING

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CERTIFICATE

This is to certify that the work which is being presented in this report entitled, "**EVALUATION AND IMPROVEMENT OF NON-BONDED PIEZO SENSOR (NBPS) FOR BIO-MEDICAL STRUCTURAL HEALTH MONITORING (BSHM) USING EMI TECHNIQUE**" which is being submitted by **SHIPRA PRAKASH** (**ENTRY NO: 2018CES2182**) in the fulfilment the requirements for the award of degree of Master of Technology in "**STRUCTURAL ENGINEERING** " is a record of the student's own work carried out at **INDIAN INSTITUTE OF TECHNOLOGY (IIT) DELHI, INDIA** under my supervision and guidance.

The matter embodied in this thesis has not been submitted elsewhere for the award of any other degree or diploma.

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Shipra

SHIPRA PRAKASH

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ABSTARCT

Human health has always been the greatest concern in view of its wellbeing as we human are responsible for the changes, development and upliftment of society and nation. Since many years, tremendous research efforts have been undertaken for humanity's growth, wellbeing and prosperity. During past few years, the integration of smart materials in the fields of biomechanics and bio-medical engineering attracts many researcher's interest. Smart materials, being miniature in size and shape and light weight, are the best suited for bio-medical structural health monitoring (BSHM). Development of low-cost non-invasive techniques for long-term and continuous monitoring of critical organs has recently become a major area of interest to many academic and medical laboratories. Use of smart materials is important in view of the fact that some of the existing bone diagnosis techniques, such as Dual X-ray absorptiometry (DEXA) are hazardous in nature.

This project work focused on enhancement of a previously developed technique non-bonded piezo sensor configuration as a diagnostic technique for non-invasive detection of fractures and physiological decay of bones by disease such as osteoporosis, using lead zirconate titanate (PZT) patches in the framework of the electro-mechanical impedance (EMI) technique. In this technique, improvements were done in clamping methods to make it easily wearable and to standardize the degree of clamping in terms of more easily measurable parameters. Use of Torque wrench in place of complex electrical equipments such as ESGs and DMM for tightening the NBPS was undertaken to make technique user friendly and cost effective. The enhanced approach will be addressed as one electro-mechano gram (BEMG). As in the previous approach, the PZT patch was used in non-bonded configuration by adhering it on a small aluminum strip referring whole as NBPS strip. For laboratory validation this strip was then clamped on artificial human femur made up of polyvinyl chloride (PVC) through various clamping methods. Two artificial femur bones were used as specimens, one as healthy and other osteoporotic by drilling holes in it with desired dimensions and numbers. For clinical validation, the clamp was tested on five live subjects. DEXA scanning of the live subjects was performed at Indian Spinal Injury center (ISIC) located at Vasant Kunj area in New Delhi, the results thus obtained compared with the BEMG tests results in laboratory. It was found that the healthy subjects displayed series k-m-c system. Hence, NBPS has strong potential to substitute the currently prevalent DEXA, which is hazardous in nature.

LIST OF ACRONYMS

BSHM	Biomedical Structure Health Monitoring
DEXA	Dual Energy X-Ray Absorptiometry
DBPS	Directly Bonded Piezo Sensor
EMI	Electro Mechanical Impedance
FRF	Frequency Response Function
LCR	Inductance Capacitance Resistance
PVC	Polyvinyl Chloride
PZT	Lead Zirconate Titanate
MDF	Modal Damping Factor
NBPS	Non-Bonded Piezo Sensor
SDOF	Single Degree of Freedom
SHM	Structure Health Monitoring
BEMG	Bone electro-mechano gram
EDP	Effective Derive point

LIST OF SYMBOLS

A	Area
B	Susceptance
D_3	Dielectric displacements along axis 3
d_{ij}	Piezoelectric strain coefficient of PZT patch
E	Modulus of elasticity
E_3	Electric field along axis 3 of PZT patch
G	Conductance
G_0^i	Pre - damage conductance for ith frequency point
G_i^1	Post - damage conductance for ith frequency point
h	Thickness of PZT patch
k	wave number
l	length of PZT patch
n	number of readings
S_1 (S_i)	Mechanical strain along axes 2 (1)
T	Temperature
T_1 (T_i)	Mechanical stress along axes 2 (1)
u	Displacement at the interface between the bonding layer and the beam
w	width of PZT patch
$\overline{Y}$	Complex electro mechanical admittance (G+Bj)
Y_a	Active admittance
$Y_{i,1}$	original impedance at frequency interval i
$Y_{i,2}$	interrogated impedance at frequency interval i
Y_p	Passive admittance
$\overline{Y^E}$	Complex Young's Modulus of elasticity
Z	Complex mechanical impedance of
Z_a	Mechanical impedance of the PZT
Z	Complex permittivity of the PZT patch for axes i and j at constant stress
ρ	Density
ω	Angular frequency
υ	Poisson ratio

δv	vertical shift
ΔH	Horizontal shift
ΔV	Vertical shift

LIST OF FIGURES

CHAPTER 1

INRODUCTION

1.1 BACKGROUND

Human health has always been a prime factor of concern in view of its development, societal development or in more extent, the development of a Nation. In this regard, people engaged in studies of Medical sciences has been putting their greatest efforts to study, to diagnose, to enhance and improve human health by incorporating many advance technologies. For an instance, let us shifted our focus on technologies used for diagnosing ailments and in human bones those are X-Ray, CT Scan, DEXA etc.

Dual energy x-ray absorptiometry (DEXA) or bone densitometry, is an enhanced form of x-ray technology that is used to measure bone mineral loss. Since its development to till now it is working well, fully serving its purpose. DEXA is made easily available in hospitals and scan centres. Apart from its advantageous performance, some key issues can be penned down as drawbacks like emissions of X-rays, exposure of which on human body is harmful indeed, specially for children and senior citizens and sometimes it has been proven uneconomical for underprivileged section of society.

In this project, an attempt has been made to enhance a previously developed device which can be used for detection of mineral loss in bones, known in medical term as Osteoporosis, based on technology which is being in use for health monitoring of civil and mechanical based structures (SHM). Advantages of this device can be noted as, very cheap and easily handled, no x-ray exposure of the humans and proved to be a quick method for diagnosis of disease like Osteoporosis.
Everything discussed above will be covered in detail in subsequent sections of this thesis.

1.1.1 Structural health monitoring (SHM)

The term structure health monitoring (SHM) usually refers to the process of a damage detection strategy for aerospace, civil or mechanical engineering infrastructure. The process involves the observation of a structure or mechanical system over time using periodically spaced dynamic response measurements, the extraction of damage sensitive features from these measurements and the statistical analysis of these features to determine the current state of system health.

SHM provides the continuous measurement of the operating environment and severe response of the structure or its components to track and evaluate the symptoms of deterioration or damage indicators that may affect the operation, serviceability, safety or reliability. SHM based on electromechanical impedance (EMI) technique, a universal cost-effective technique is in use these days. EMI technique incorporates smart materials like lead zirconate titanate (PZT) for the actuation and sensing purpose.

Based on the amount of information provided regarding the damage state, Farrar and Jauregui (1998) defined four distinct objectives of structural health monitoring as

- To ascertain that damage has occurred or to identify the damage.
- To locate the damage.
- To determine the severity of damage.
- To determine the remaining useful life of the structure.

1.1.2 Bio-medical structural health monitoring (BSHM)

When the available SHM technologies are applied in the field of bio-mechanics and bio-technology, the domain is called as bio-medical structural health monitoring (BSHM). There is a high demand for non-invasive techniques in medical science for investigating the health of a patient while ensuring minimum discomfort and pain to the subject. Considering this aspect, this thesis presents the work involving extension of SHM technologies (involving piezo materials) to bio-system encompassing, bio-mechanics and bio-medical engineering. The system used in this project are artificial human femur bones made of poly vinyl chloride. An attempt has been made to detect the osteoporotic condition of bone through EMI technique.

1.2 OBJECTIVES AND SCOPE OF THE PROJECT

Main objective of this project is to improve non-bonded piezo sensor (NBPS) for diagnosis and quantification of deterioration in human bones. In this project osteoporosis, which represents loss in bone mineral density is considered as damage in bones and of prime factor of concern for its detection using advanced SHM technologies involving EMI technique and PZT patches. Experiments are performed on both healthy and osteoporotic bones (lab specimens of PVC) in different clamping conditions i.e. bonded and non-bonded piezo sensors with different degree of clamping have been used in experiments for a better comparative study. Earlier method of clamping incorporated usage of complex electrical equipments such as electrical strain gauges and digital mulitimeter and hence improvement in clamping methods are required in order to make the technique easily accessible. Finally testing on live subjects is done in order to validate the laboratory results against clinical findings.

1.3 ORGANIZATION OF THESIS

This thesis consists of Eight chapters. After list of contents the list of figures, table, symbols, and abbreviation are specified. The notations have been well defined at the place where they first appear. The content of each chapter is briefed below.

Chapter 1: This chapter covers the brief introduction of SHM and BSHM followed by project objective and scope.

Chapter 2: This chapter contains of the state-of-art of EMI technique and BSHM followed by Identification of research gaps. Objectives and scope are specified in detail.

Chapter 3: This chapter covers the experimental evaluation of existing system of Non-Bonded piezo sensor (NBPS) for monitoring health conditions through conductance signature of the artificial femur bones in both healthy and osteoporotic conditions and the experiments done by incorporating directly bonded piezo sensors (DBPS) on the same specimens are also shown. A comparative study of results between DBPS and NBPS configurations followed by experimental results and the concluding remarks have been discussed.

Chapter 4: This chapter covers the improvements done in clamping methodology. An attempt of making a wrist band NBPS in context of an easily wearable device is also shown in this chapter. It also covers the demonstration and implementation of improved clamping method for NBPS using torque wrench that will later addressed as bone electro-mechano gram (BEMG), as a low-cost substitution of DEXA for osteoporosis detection.

Chapter 5: This chapter covers the details of testing of live subjects in laboratory as well as in clinic followed by a comparative study on results of both the testing and conclusions have been made.

Chapter 6: This chapter covers the conclusions of various research that has been done in this project followed by some limitations and future recommendations.

Finally, References has been provided along with Appendices.

CHAPTER 2

STATE-OF-ART IN BIO-MEDICAL STRUCTURAL HEALTH MONITORING

2.1 INTRODUCTION

This chapter covers the basic details of EMI technique and Piezoelectric materials. It also covers the detailed literature review on bio-medical structure health monitoring using bonded and non-bonded piezo sensor and other conventional methods followed by research gaps and research objectives.

2.2 PIEZOELECTRICITY AND PIEZOELECTRIC MATERIALS

Piezoelectricity is the ability of crystals and certain ceramic materials to generate a voltage in response to applied mechanical stress. The piezoelectric effect is reversible in that piezoelectric crystals, when subjected to an externally applied voltage, can change shape by a small amount. **Lead zirconate titanate** (Pb[Zr*x*Ti1-*x*]O3 0<*x*<1) is a ceramic perovskite material that shows a marked piezoelectric effect. It is also known as lead zirconium titanate or PZT, an abbreviation of the chemical formula. Being piezoelectric, it develops a voltage difference across two of its faces when compressed (**sensor**), or physically changes shape when an external electric field is applied (**actuator**) as shown in Fig. 2.1. The material features an extremely large dielectric constant at the morphotropic phase boundary (MPB). These properties make PZT-based compounds one of the most prominent and useful electro ceramics.

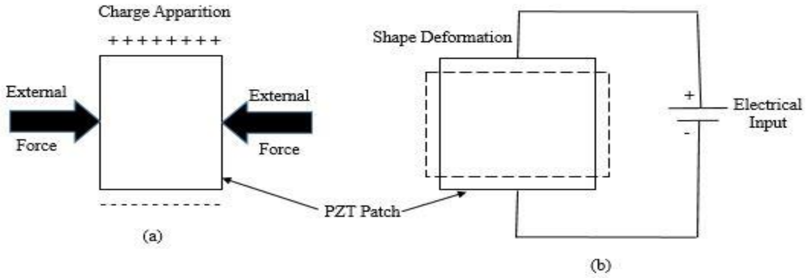


Figure 2.1: PZT under (a) Direct effect (sensor),
(b) converse effect (actuator)

2.3 ELECTROMECHANICAL IMPEDANCE (EMI) TECHNIQUE

The EMI was first invented by Liang et al. (1994). This technique employs PZT patches to measure the structural dynamic response continuously in the form of admittance signatures. The PZT patches are bonded to the structure by means of high strength epoxy and act as both sensors and actuators simultaneously.

The basic principle behind this technique is to apply high frequency structural excitations (usually > 30 kHz) through surface bonded PZT patches. On being subjected to an alternating electric field, the patch undergoes harmonic deformations and thus generates local mechanical vibrations in the structure. The response of the structure is then relayed from the patch as an electric signal, namely the admittance as shown in Fig. 2.2.

Admittance, as a function of frequency, forms a unique benchmark fingerprint signature of the structure, carrying information pertaining to dynamic characteristics of the structure. Any damage occurring in the structure alters the signature and this serves as an indication of damage. On analysis of the signature at any point of time, occurrence of damage can be easily detected as a change in the admittance signature of the patch from the baseline measurement. Liang (1994) proposed a 1D analytical model of Electro-Mechanical Impedance as shown in Fig. 2.3

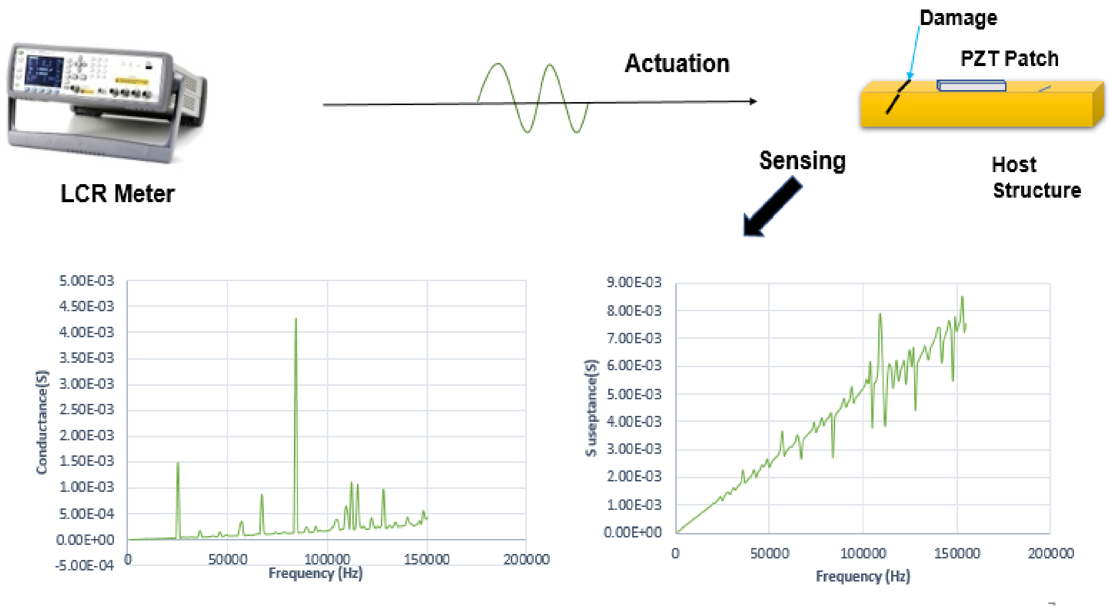


Figure 2.2: EMI Technique

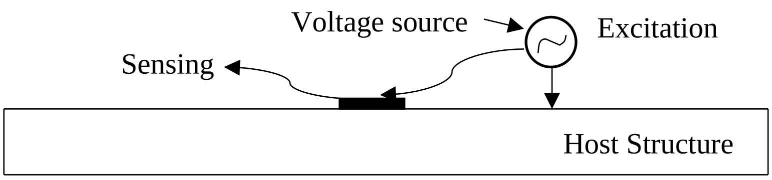


Figure 2.3: Schematic representation of Liang's Model

The governing one-dimensional wave equation for the generic system comprising one half of the patch and the structure has been solved by Liang et al. (1994) using the impedance approach.

$$\bar{Y} = 2\omega j \frac{wl}{h}\left[\overline{\varepsilon_{33}^{T}} + \left(\frac{Z_a}{Z+Z_a}\right) d_{31}^2 \overline{Y^E}\left(\frac{\tan \kappa l}{\kappa l}\right) - d_{31}^2 \overline{Y^E}\right] \tag{2.1}$$

$$\bar{Y} = G + Bj \tag{2.2}$$

where d_{31} is the piezoelectric strain coefficient, $\overline{Y^E}$ the complex Young's modulus of the PZT patch at the constant electric field, $\overline{\varepsilon_{33}^{T}}$ the complex electric permittivity of the PZT material at constant stress, Z the mechanical impedance of the structural system, ω the angular frequency, l, w ,h are length, width and height of the PZT patch and κ the wave number and Z_a is the actuator impedance, given by

$$Z_a = \frac{kh_p w\overline{Y^E}}{\tan kl(j\omega)} \tag{2.3}$$

The mechanical impedance Z is a function of the structural parameters, *i.e.*, the stiffness, damping, and mass. Any damage to the structure will cause these parameters to change and hence improves the drive point mechanical impedance Z. Consequently, as can be observed from the equation, the electro-mechanical admittance, $\bar{Y}$ will undergo change, and this serves as an indicator of the state of health of the structure.

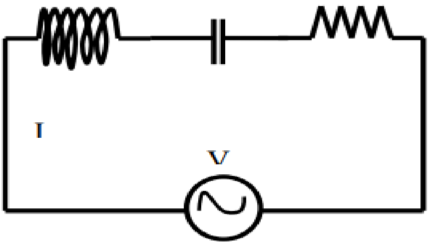
Bhalla and Soh (2003) showed in their work, the relevance of the imaginary component by introducing the concept of "Active Signatures" i.e. The contribution of a PZT patch i.e. the passive part of raw admittance signature, in the acquired signature can be filtered off, so that the remaining signature will reflect only the behaviour of the structure and hence proved that the active part is more contributing in EMI technique of the structure.

On analysis, it is found that a single degree of freedom (SDOF) spring-mass-damper system is mathematically analogous to a series LCR circuit in the classical electricity. The instantaneous velocity term is analogous to the current and the mechanical force is analogous to electromotive-force (voltage).

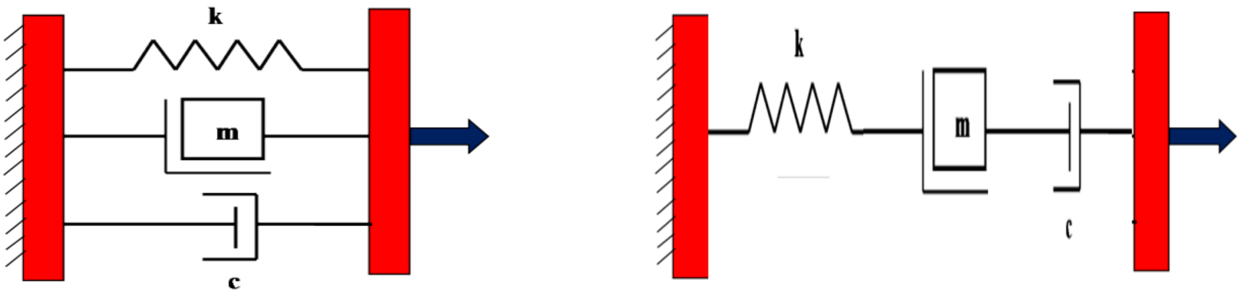
The damper is analogous to the resistor, mass is analogous to the inductor and the spring is analogous to the capacitor.

The basic elements viz the mass, the spring and the damper can be combined in several different ways (series, parallel or mixture) to evolve complex mechanical systems, two such ways are shown in Fig. 2.4 (a) and (b).

Applying the principle of active and passive signature decomposition, the mechanical impedance of the host structure can be determined from the admittance signatures of the surface bonded PZT patches **(Bhalla and Soh, 2004b).** Detail procedure and differential equations involved in impedance extraction is given in Appendix B.



(a)



(b)

Figure: 2.4 (a) Electrical circuit analogous to SDOF spring mass system

(b) Parallel and series connection of basic components

2.4 CONVENTIONAL TECHNIQUES AND SMART MATERIALS SO FAR IN BSHM

Capsule build up around soft tissue implants in Sprague-Dawley rats was demonstrated through embedded PZT patches based on EMI technique **(Bender et al., 2006).** Also, the utilization of piezoelectric sensors in plastic surgery was studied. The vibrational amplitude at a frequency corresponding to radial resonance changed with variation in the viscous dissipation of the tissue easily captured by the implanted PZT patch through changes in conductance signature.

It is an established fact that the health of bones can be assessed from their mechanical properties, such as the density and the Young's modulus, which show reasonable change with bone condition **(Erickson et. al., 2002; Ritchie et. al., 2006)** and hence attracted a special interest because condition of bones can be determined by determining the mechanical properties of bones. Bones undergo slow but continuous restructuring as a part of normal biological ageing. They may also go undergo abrupt changes under diseased conditions, such as osteoporosis, which is accompanied with the loss of bone density, stiffness and ductility.

Christolpolu et. al. (2006) reported the measurement of modal damping of bones of adult female Wister rats using accelerometers. They had shown that the non-invasive Modal Damping factor (MDF) methodology may helpful as diagnostic tool for bone ailments.

Accelerometer is a mechanical or electro-mechanical device that measures the rate of increase or decrease in the velocity of a moving object. Its basic components are a mass, damper and a spring that result in a second order lumped physical system. The basic principle of an accelerometer is that the displacement of a small proof mass due to a force applied on it is proportional to acceleration, provided the frequency being measured is much smaller than the natural frequency of the system. Accelerometers are used in heart pacemakers and defibrillators, patient monitoring equipment, blood pressure monitors and Diagnostics of various other bio-medical applications. Their limitations are that they are relatively bulky, fragile, expensive and may be contaminated by components of gravity.

Bajaj et. al. (2006) reported the first of its kind experiment on a chicken femur involving PZT patches. Two PZT patches, 10 X 10 X 0.3 mm in size, were bonded near two ends of the femur While one PZT patch acted as actuator, the other acted as sensor. Frequency response function (FRF) in terms of the ratio of the output to input voltage was employed as bone's signature. They demonstrated the possibility employing the gain based FRF to detect any changes occurring in the conditions of bones, from the shift of modal frequencies and the changes in modal damping.

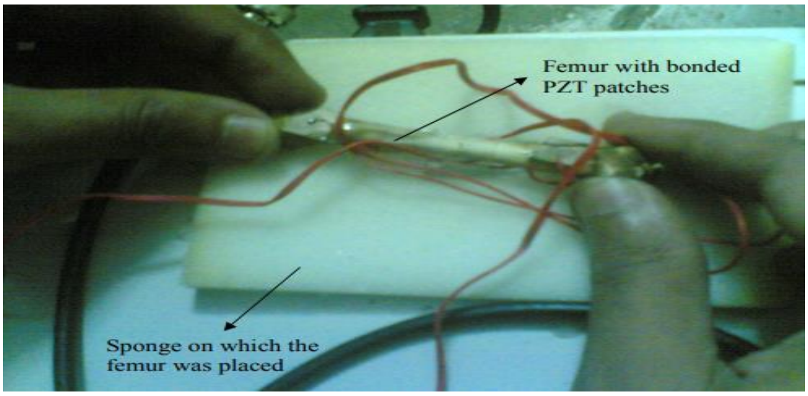


Figure 2.5: PZT Transducer bonded on chicken femur (Bajaj et. al. ,2006)

Bhalla and Suresh (2013) explored monitoring conditions of bones using directly bonded piezo sensors (DBPS). The bones underwent varying conditions like density changes, appearance of cracks and fracturing. These changes resulted in change in conductance signature of the DBPS. The changes in the signature correlated well with the changes in the condition of the bones.

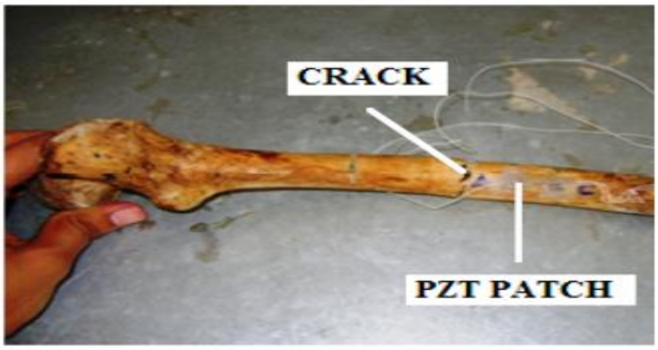
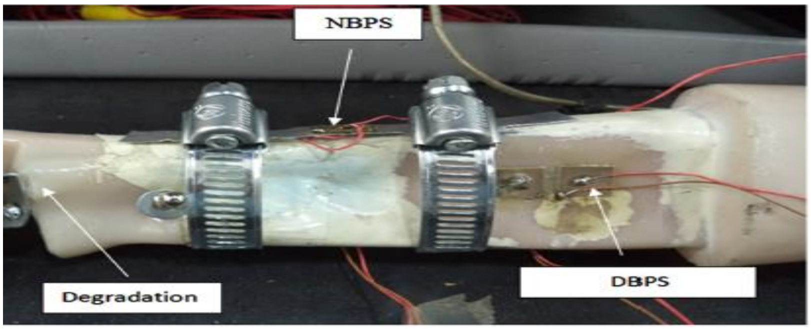


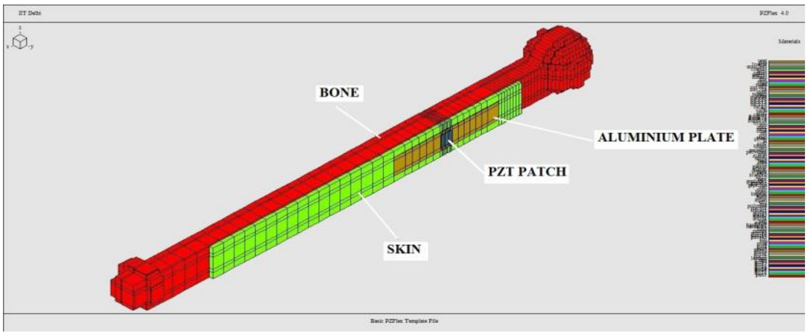
Figure 2.6: Directly bonded PZT on femur (Bhalla and Suresh ,2013)

Bonding of PZT patches directly on the human bones is not desirable since it involves live human subjects hence bonding is not feasible in such cases. Several attempts has been made in regard of non-bonded configuration of piezo sensors with high sensitivity and effectiveness in signatures.

Srivastava et. al. (2017) reported the development of a new non-bonded piezo configuration, namely NBPS which is a reusable sensor that could be applied on live subjects, based on the EMI technique since the system is bio-compatible for health monitoring of live subjects including human beings. He also successfully investigated the effect of skin and other muscular tissues on the NBPS effectiveness and experimentally showed that there is not much loss of sensitivity of signature in the presence of the skin or the underlying cartilage/ fat layer. He had also developed a numerical model to validate the experimental results and found the satisfactorily compatibility between both.



(a)



(b)

Figure 2.7: (a) NBPS configuration of PZT to monitor bone health (Shrivastava et. al., 2017) (b) Numerical Model of Bone with NBPS (Shrivastava et. al.,2019)

2.5 IDENTIFICATION OF RESEARCH GAPS

Research gaps found after the literature review are as follows:

1. Clamping methods need improvements for better effectiveness of NBPS on live subjects with minimum discomfort to the person.
2. Previously developed Non bonded piezo sensor to monitor the condition of bones has not been validated against clinical results. Only laboratory results of Artificial Bones are available right now.
3. For the better diagnosis and prediction of bone health condition, a greater number of trials on live subjects are needed.

2.6 RESEARCH OBJECTIVES

Following objectives have been addressed in this master's project.

1. To improve and simplify evaluate non-bonded piezo sensor configuration for BSHM.

2. To experimentally establish the effectiveness of the NBPS configuration vis-à-vis the DBPS configuration.

3. To explore damage and osteoporosis detection in bones without needing baseline signature.

4. To validate the laboratory results with the clinical findings by doing experiments on live subjects.

CHAPTER 3

ENHANCEMENT AND EXPERIMENTAL EVALUTION OF NON-BONDED PIEZO SENSOR(NBPS) VIS-À-VIS DIRECTELY BONDED PIEZO SENSOR (DBPS) CONFIGURATIONS

3.1 INTRODUCTION

As reported in the previous chapters, research on bio-medical applications of PZT patches was employed the adhesively bonded piezo configuration for diagnostics prior to the introduction of NBPS (Srivastava, 2017) and Hence, NBPS development paved the way for an entirely new concept of incorporating non-bonded piezo application for BSHM. This chapter covers in detail, the method of evaluation of existing system of NBPS and basic experiments to explore its feasibility and effectiveness on artificial human femur bones made up of polyvinyl chloride (PVC) followed by evaluation by directly bonded piezo sensor configuration. This chapter also shows the theoretical validation of laboratory results thus obtained. An attempt to make NBPS easily wearable i.e. development of new wrist band NBPS using women's wrist watch is also shown in this chapter.

3.2 IMPROVED CONFIGURATION OF NON-BONDED PIEZO SENSOR

Previously designed NBPS (Shrivastava, 2017) consisted of an aluminium strip, 92×15×1mm in size, on which a PZT patch, 10×10×0.3 mm in size, conforming to grade PIC 151 (PI Ceramic, 2014) was bonded at the midpoint using two-part araldite epoxy adhesive.

Following the same pattern, for this project, a NBPS consisted of similar aluminium strip but different in size i.e. 70×10×1mm on which above mentioned PZT is bonded in similar fashion, as shown in Fig. 3.1, reason behind the modified dimensions can be seen as a method of improving effectiveness in signatures of bones before and after damage as aluminium strip also contributes some additional frequency peaks which might have confused with structural peaks.

Two jubilee clamps were then used to clamp the aluminium strip on the test specimen i.e. artificial bone, thereby creating the non-bonded configuration, as shown in Fig. 3.2. The jubilee clamps carry a mechanism of screws which can be turned to tighten the clamps to achieve the desired level of strain i.e. 300 microns (Shrivastava, 2017) measured by similar strain gauges attached on both the clamps and strain was measured incorporating the empirical formula as given in Eq. 3.1. An identical PZT patch was directly bonded to the bone in conventional DBPS configuration as shown in Fig.3.10 The artificial bone taking as test specimen for the project was a human femur bone made of polyvinyl chloride.

(a) **(b)**

Figure 3.1: (a) NBPS strip (b) Healthy and osteoporotic bones

3.3 LABORATORY TESTING OF NBPS

3.3.1 Experimental setup to acquire admittance signatures of bones using NBPS

NBPS was clamped on healthy and osteoporotic bones in four different clamping conditions:

- Free-free (only NBPS)
- Open clamped (at zero strain)
- Partially clamped (at 160 µm/m; Srivastava, 2017)
- Fully clamped (at 300 µm/m; Srivastava, 2017)

Experimental setup consisted of NBPS clamped on bone using jubilee clamps and strain gauges instrumented on both clamps to measure desired strain as mentioned above, using digital multimeter as shown in Fig. 3.2 (a) and (b).

After tightening the clamps at desired strains, test specimen was attached to an LCR metre (model E4980, Agilent Technologies, 2014) and signatures were acquired using VEE PRO 9.3 software operating on a personal computer in laboratory-controlled environment as shown in Fig. 3.3

(a) **(b)**

Figure 3.2: (a) NBPS clamped on bone using two jubilee clamps

(b)laboratory setup for finding strains in clamps using digital multimeter

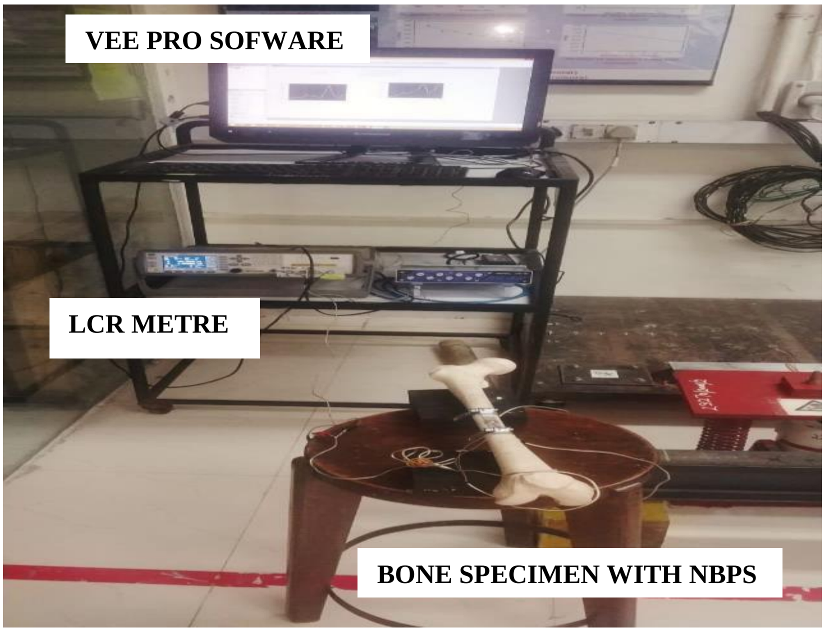
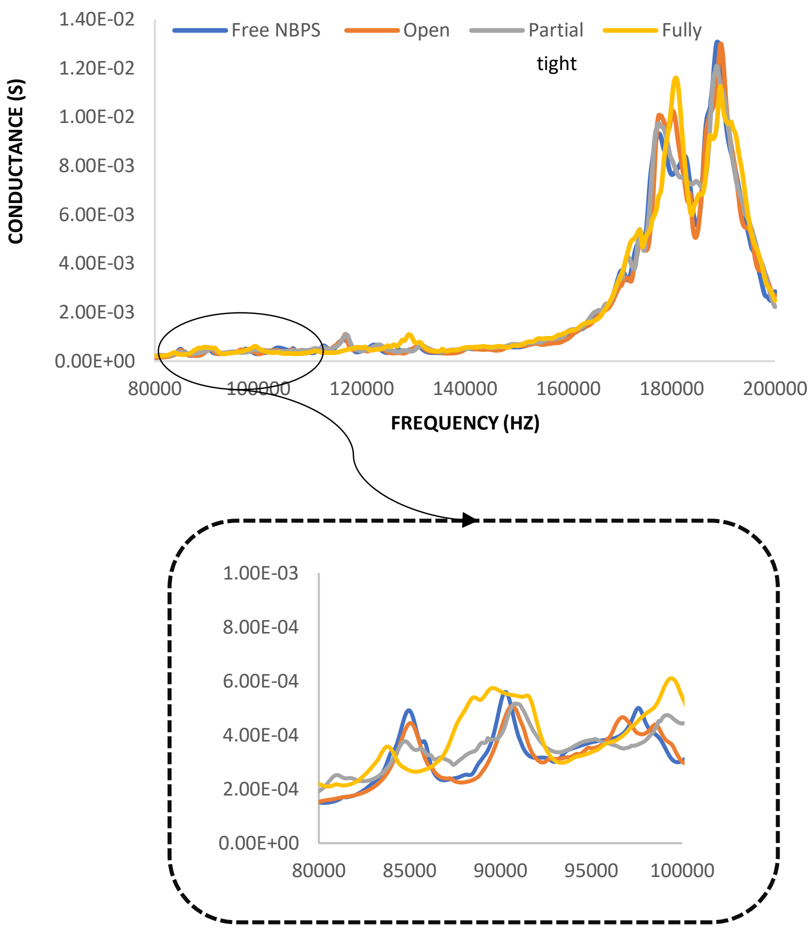
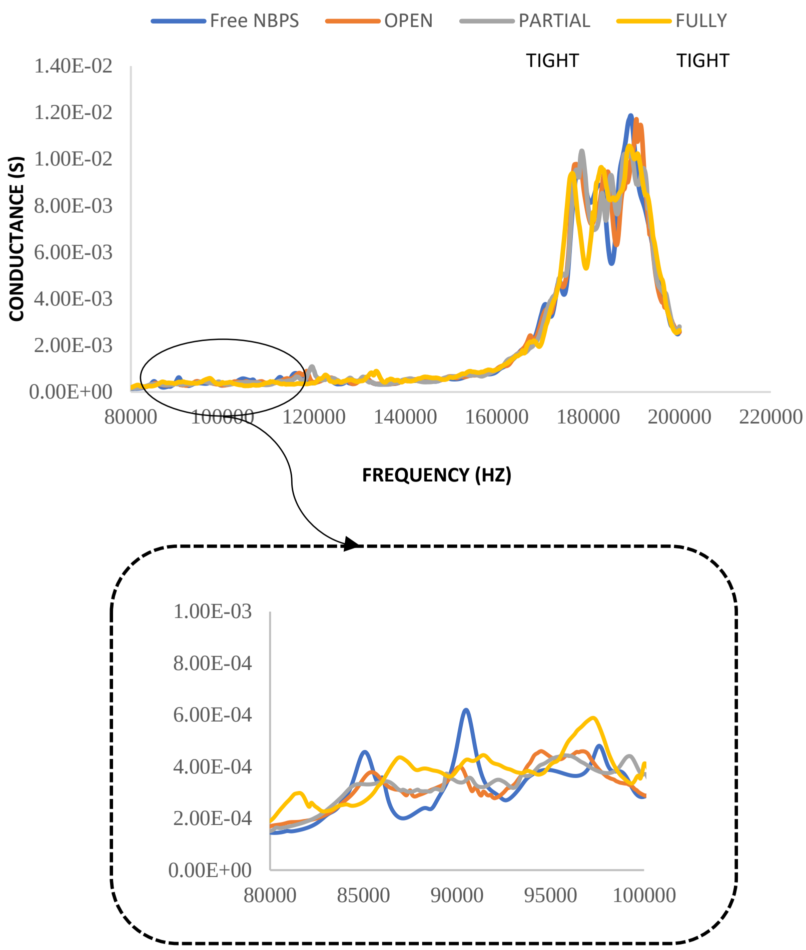


Figure 3.3: Laboratory setup to acquire signature of bones.

3.3.2 Observations and results



(a)



(b)

Figure 3.4: (a) NBPS signatures for Healthy bone in four clamping conditions
(b) NBPS signatures for Osteoporotic bone in four clamping conditions

3.3.3 Comparison of NBPS signatures bonded on healthy and osteoporotic bones

From Fig 3.4 (a) and (b), following observations are made

1. Shift in frequency peaks can be clearly seen in the conductance signatures shown in Fig. 3.4
2. Osteoporosis causes decrease in bone mineral density and hence modal frequency of damaged bone will tends to change according to the empirical relation as given in Eq. 3.1 (Chopra, 1995). Hence, feasibility and reliability of the NBPS configuration in EMI technique for physiological damage detection of bone is successfully established once again.

$$f_n = \frac{2n-1}{4L_H}\sqrt{\frac{E}{\rho}} \qquad (3.1)$$

Where L_H is the half-length of the specimen, E the Young's modulus of elasticity and ρ the bulk density of the bone.

3. Due to decrease in mass density, frequency was increased as per Eq. 3.1 thus resulting in rightward shifting of the frequency peaks of the conductance signature as shown in Fig. 3.5. This matches with the earlier observations made by Srivastava (2017)

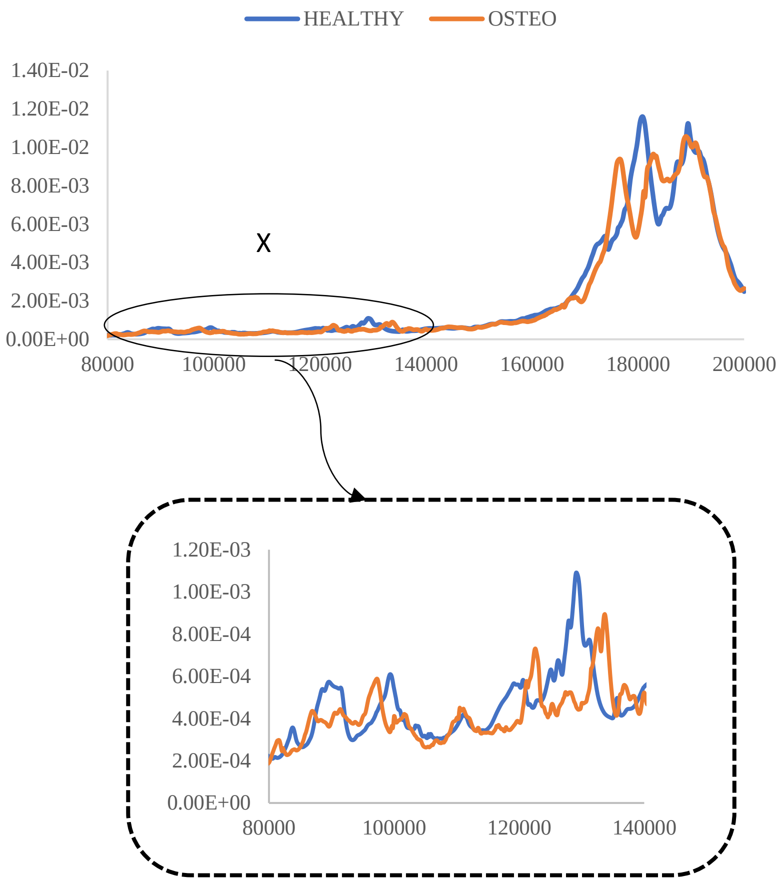


Figure 3.5: Comparison of conductance signatures of healthy and osteoporotic bones

3.4 VALIDATION OF EXPERIMENTAL RESULTS WITH THEORITICAL FINDINGS

Effectiveness of clamping can be clearly substantiated by the fact that the peak represented by PZT patch resonance (189 kHz) underwent substantial subsidence after full tightening. In addition, new peaks appear in the lower frequencies, indicating that the characteristics of the bone have started showing up in the signature. The natural frequency of the bone corresponding to the n^{th} axial mode of vibration can be theoretically determined using (Chopra, 1995) as shown in Eq. 3.1 The bulk density of the bone was experimentally determined using specific gravity instrument in laboratory as shown in Fig. 3.6. It found out to be 1367 kg/m^{3,} E value was considered as 4000 MPa for hardened PVC material (Engineering Toolbox, 2015). After substituting the values of known parameters in Eq. 3.1 an empirical relation has been derived as *2809.166* (2n-1)* Hz. Based on this relation theoretical frequencies were worked out and tabulated in Appendix A.

Fig. 3.7, Fig. 3.8 and Fig. 3.9 shows the correlation between signature peaks and theoretical frequencies (in brackets). Values in red colour shows the structural peaks other values shows the NBPS peaks.

Figure 3.6: Laboratory setup for measuring specific gravity of bone

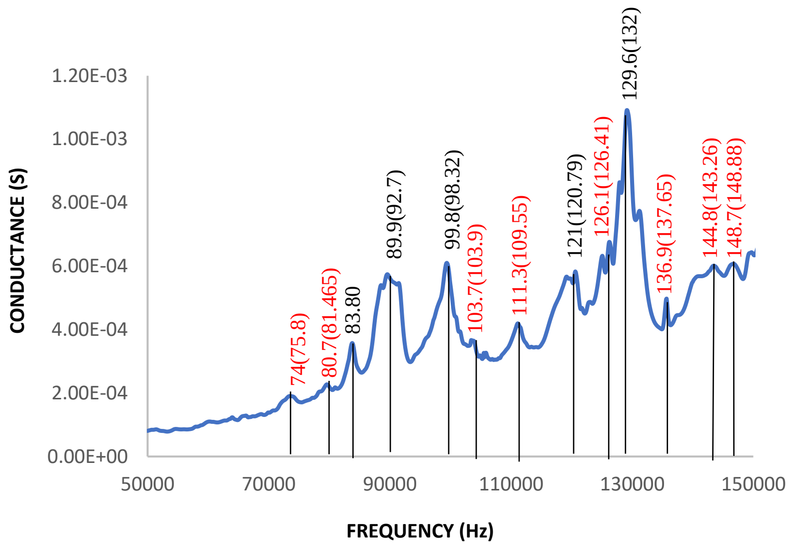


Figure 3.7: Correlation between experimental and theoretical frequencies (in kHz) of Healthy Bone (theoretical frequencies in brackets)

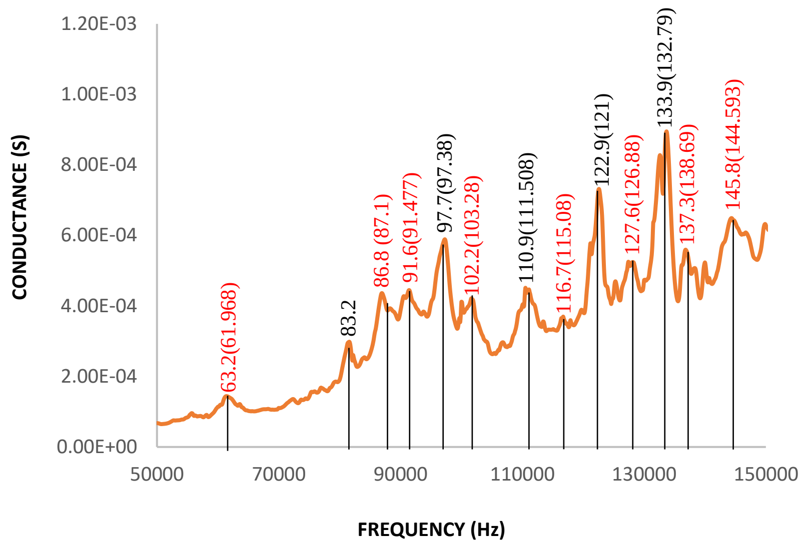


Figure 3.8: Correlation between experimental and theoretical frequencies (in kHz) of Osteoporotic Bone (theoretical frequencies in brackets)

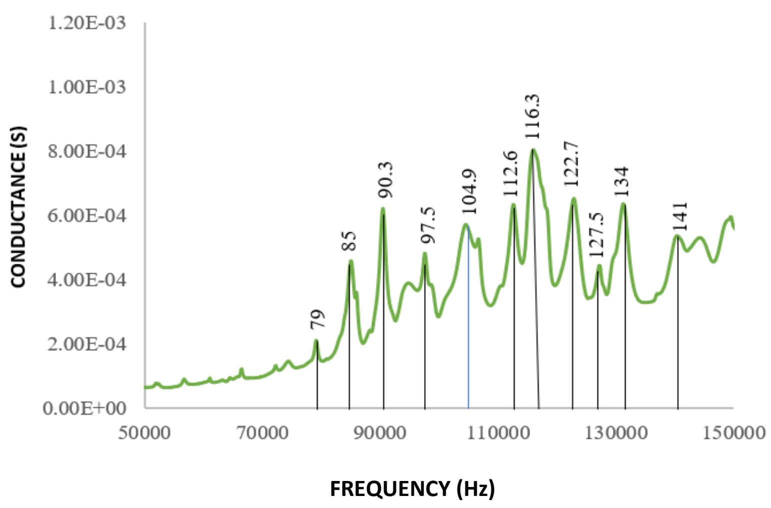


Figure 3.9: Correlation between experimental and theoretical frequencies (in kHz) of Free NBPS strip (theoretical frequencies neglected)

3.5 DEVELOPMENT OF DIRECTLY BONDED PIEZO CONFIGURATION

A PZT patch, 10×10×0.3 mm in size, conforming to grade PIC 151 (PI Ceramic, 2014) was bonded at the midpoint using two-part araldite epoxy adhesive as shown in Fig 3.10

After bonding the PZT patch test specimen has been attached to an LCR metre (model E4980, Agilent Technologies, 2014) and signatures were acquired using VEE PRO 9.3 software operating on a personal computer in laboratory-controlled environment as described in earlier chapters.

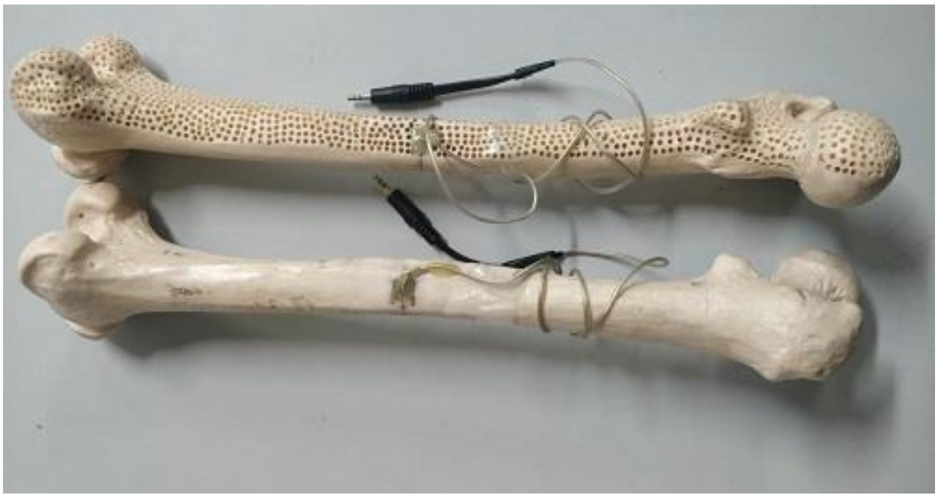


Figure 3.10: DBPS configuration of PZT on healthy and osteoporotic bones.

3.6 EXPERIMENTAL EVALUATION OF DBPS CONFIGURATION

Fig. 3.11 shows the acquired signature of healthy and osteoporotic bones through DBPS configurations.

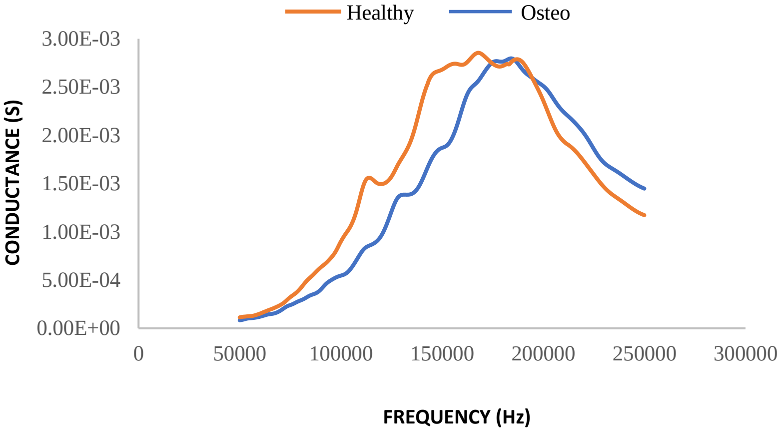
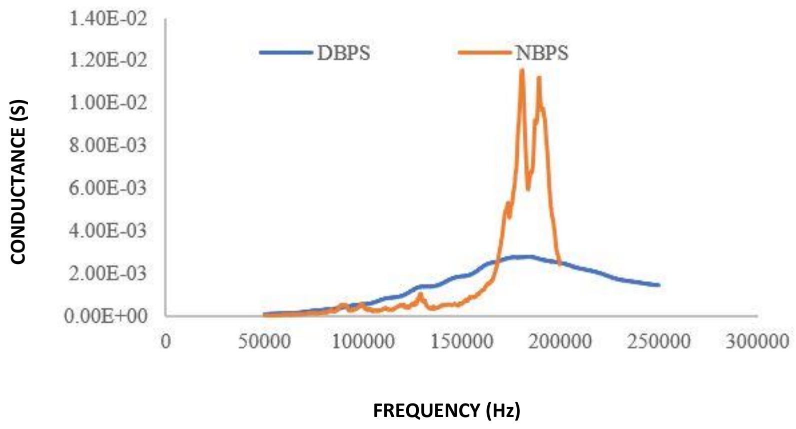
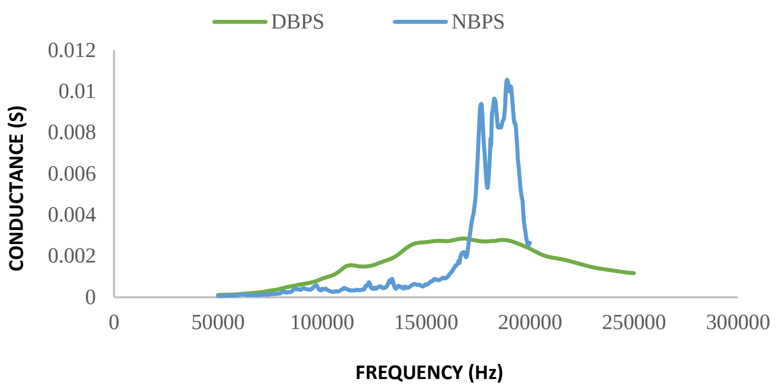


Figure 3.11: Conductance signature of healthy and osteo bones in DBPS configuration



(a)



(b)

Figure 3.12: comparison of conductance signature of DBPS and NBPS for

(a) Healthy bone

(b) Osteoporotic bone

Fig. 3.12 (a) and (b) shows the variation in signatures in DBPS and NBPS configurations of PZT patch. From the figures it can be seen that DBPS configuration sometime gives "Peak free signatures" may be due to high damping caused by Bone material i.e. PVC and hence difficulty in identifying structural peaks rather NBPS peaks are identifiable.

3.7 DEVELOPMENT OF NEW WRIST BAND NBPS USING WOMENS' WRIST WATCH

Above mentioned clamping method also has its limitations as it involves complex electrical equipments corresponds for measuring desired strain. Hence moving forward, an attempt was made for improved clamping.

A wristwatch was used with a base plate thickness of 7mm, a PZT patch, 10×10×0.3 mm in size, conforming to grade PIC 151 (PI Ceramic, 2014) was bonded with epoxy as shown in Fig. 3.13

Figure 3.13: A wrist band NBPS

3.8 LABORATORY TESTING OF WRIST BAND NBPS

3.8.1 Experimental setup

The newly developed wrist band NBPS was clamped on bones and signatures were acquired through VEEPRO software as mentioned in earlier chapters. Experimental setup to acquire signature is shown in Fig.3.14.

Figure 3.14: Laboratory setup for acquiring specimens' signatures

3.8.2 Observations

Fig. 3.15 shows the shifts in conductance signatures of wrist band NBPS clamped on healthy and osteoporotic bones. Horizontal and vertical shifts can be seen easily from the figure.

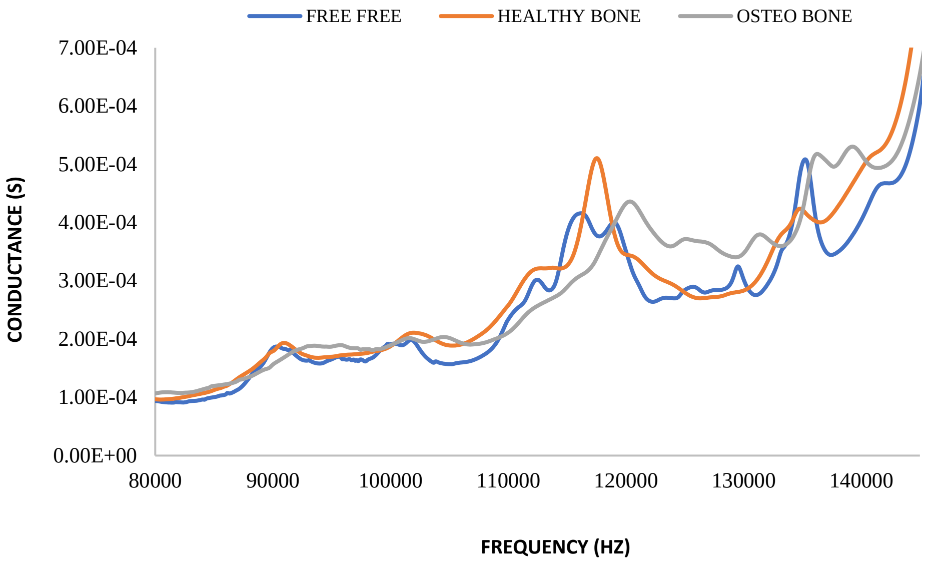


Figure 3.15: Shifts in conductance signature

3.9 CONCLUDING REMARKS

NBPS configuration once again proves its feasibility in finding bone damages through EMI technique. Peaks are not identifiable in DBPS configurations because of very high damping of bone material. Also, in real life it is impossible to attain DBPS configuration on human bones hence this configuration is overruled. From this we can conclude that effectiveness of NBPS configuration is appreciable in detecting damages in bones. Validation of experimental findings against theoretical results is successfully established. Wrist watches are easily wearable on hands hence development of wrist band NBPS is a positive step regarding development of low-cost hand wearable NBPS. Also, its signatures showed encouraging results in distinguishing Osteoporotic bone from healthy bone.

CHAPTER 4

EVALUATION OF BONE ELECTRO-MECHANO GRAM (BEMG) AS A LOW-COST SUBSTITUTION OF DEXA FOR OSTEOPOROSIS DETECTION

4.1 INTRODUCTION

Currently available dual-energy x-ray absorptiometry (DEXA) technique, being widely used for measuring bone mineral density and detecting osteoporosis disease in bones, has a working principle based on X-ray technique. X-ray involves exposure of human beings to high dose of radiation that can cause damage to tissue, for example, skin burns and eye lens cataract. Blurring of image owing to inadvertent movement of subject is also very common. Also, DEXA has proven as an expensive technique to many underprivileged people in developing countries like India. Human skeleton, a supporting framework, exhibits structural properties e.g. Mass, Stiffness, Damping, Modulus of elasticity, poisons ratio etc. making it suitable for detection of physiological damage/deformities employing EMI technique using PZT patches which are light weight, portable and less expensive. In current state-of-art, DBPS and NBPS configurations have been employed to serve the purpose of detecting osteoporosis in human bones experimenting on artificial Bones made up of Polyvinyl chloride (PVC). NBPS configuration is successfully adopted as a non-invasive technique, referred as Bone Electro-Mechano Gram (BEMG) hence paving the way of path ahead for development of easily available and affordable device for detecting ailments in human bones. This chapter showed the work done for achieving better mechanical interaction between the BEMG and artificial human bones by using torque wrench as an improvement to earlier research work where electrical strain gauge and digital multimeter were employed to establish maximum tightening to acquire the repeatability of conductance signatures.

4.2 EVALUATION OF BONE ELECTRO-MECHANO GRAM (BEMG)

The current state-of-art of the technique demonstrated by **Srivastava and Bhalla, 2017** proposed the mechanism of tightening of NBPS by using two jubilee clamps through screw followed by measuring strain to quantify the strain achieved in clamps for maximum tightening using electrical strain gauges and digital multimeter. Involvement of complex electrical equipments and usage of electricity has again proved to be cumbersome and uneconomic one. To make the technique user friendly and economically feasible, subsequent work demonstrates the use of easily available torque wrench (ISO 9001:2008; PVTR-100; 2.5-11 Nm) for tightening the NBPS using two similar jubilee clamps, naming the technique as Bone Electro-Mechano Gram (BEMG). The amount of torque applied for attaining maximum tightening and repeatability of signatures was started from 3 Nm onwards. After performing various laboratory experiments, it was observed that applied torque of 6 Nm shows good repeatability of signatures and successfully detects the osteoporotic condition of bone by showing significant horizontal and vertical shifts of signatures with respect to the healthy bone signatures. BEMG was developed in similar fashion as stated in chapter 3 i.e. it consisted of an aluminium strip, 70×10×1mm in size, on which a PZT patch, 10×10×0.3 mm in size, conforming to grade PIC 151 (PI Ceramic, 2014) was bonded at the midpoint using two-part araldite epoxy adhesive as shown in Fig. 4.1a

(a)

(b)

Figure 4.1: Bone EMG in (a) Free-Free condition and (b) clamped condition

(a) (b)

Figure 4.2: (a) Torque wrench and (b) Artificial Healthy bone with BEMG and Osteoporotic bone

4.3 LABORATORY TESTING OF BEMG

4.3.1 Experimental setup

Fig. 4.2 a & b shows the torque wrench and artificial bone specimens of both healthy and osteoporotic bones on which tests were conducted respectively. Fig. 4.3 shows the detailed experimental setup wherein, the bone specimen was tied to a stand with a string of negligible mass and stiffness to attain free-free boundary conditions of bone. The BEMG was then attached to an LCR meter and excited at frequency range of 30-200 kHz (model E4980, Agilent Technologies, 2014) and signatures were acquired using VEE PRO 9.3 software operating on a personal computer in laboratory-controlled environment.

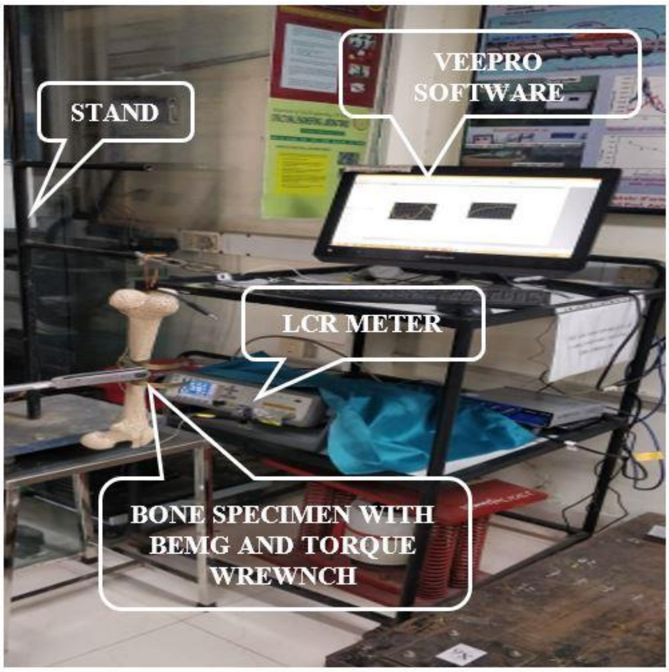


Figure 4.3: Experimental Setup

4.3.2 Observations

4.3.2.1 Effect of degree of torque applied

Fig. 4.4 and 4.5 shows the comparison of conductance signatures of BMEG at different values of torque applied to both the specimens. A well-defined shift in signature can be seen from respective figures and it can be concluded that there is significant shifting of signatures while applying torque of 3 Nm to 5 Nm whereas negligible shifting of signatures is occurred while increasing the torque up to 6 Nm, showing the maximum mechanical interaction of BEMG and bones specimens at 6Nm torque.

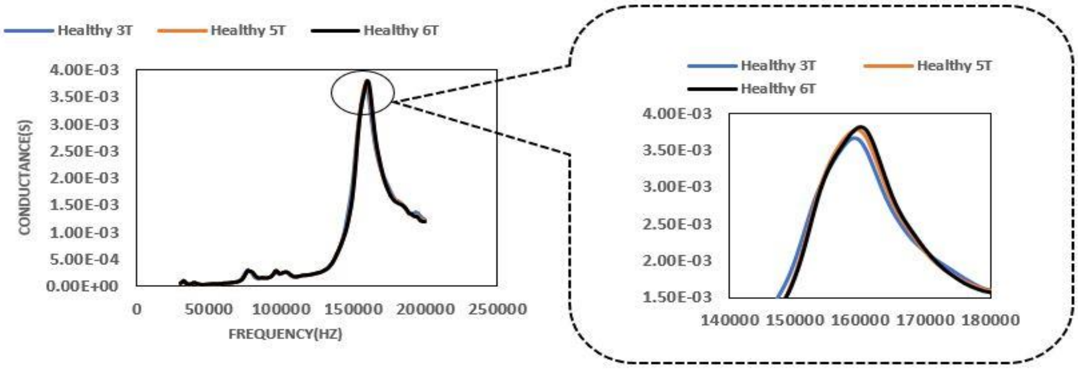


Figure 4.4: Conductance signature of BEMG clamped on healthy bone at 3 Nm (Healthy 3T), 5 Nm (Healthy 5T) and 6 Nm (Heathy 6T).

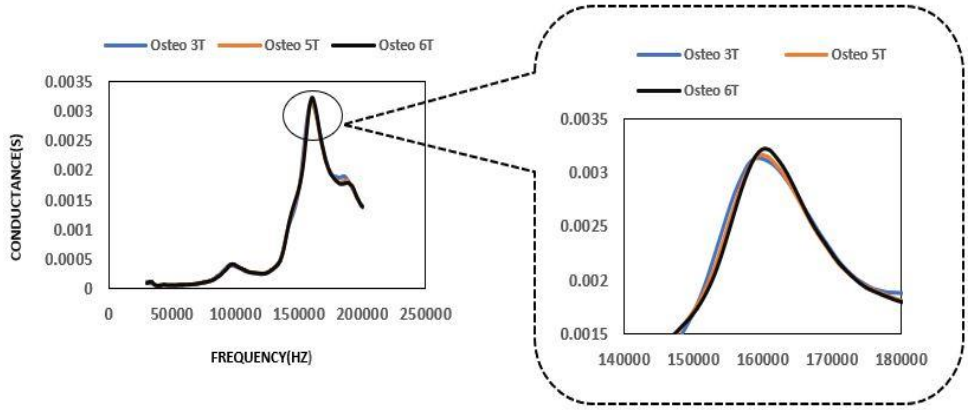


Figure 4.5: Conductance signature of BEMG clamped on osteoporotic bone at 3 Nm (Osteo 3T), 5 Nm (Osteo 5T) and 6 Nm (Osteo 6T).

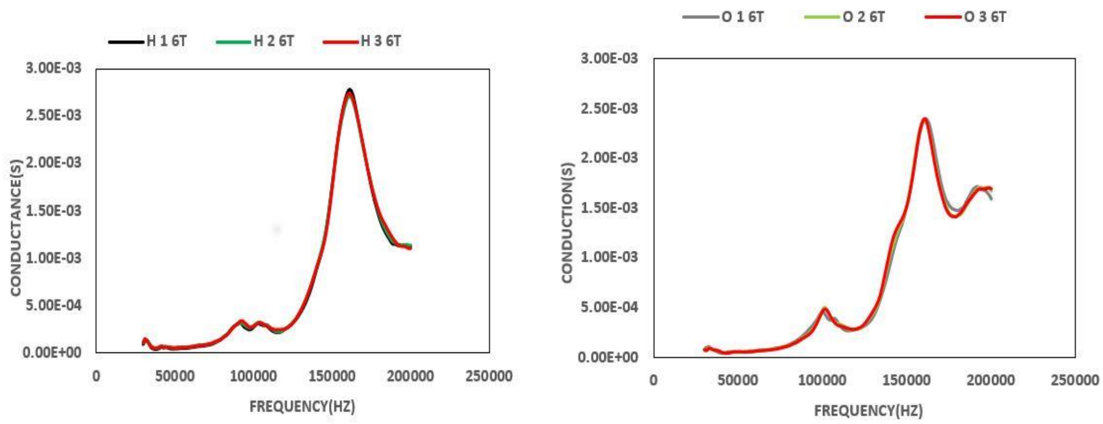


Figure 4.6: Repeatability of signatures in three trials of experiment at 6 Nm (6T) applied torque in Healthy bone (H1, H2 and H3) and in Osteoporotic bone (O1, O2 and O3)

4.3.2.2 Attainment of repeatability

Fig. 4.6 and shows the repeatability of conductance signatures of healthy and osteoporotic bones respectively, subjected to 6 Nm torque when BEMG was unclamped and taken away from its position and then again clamped to its earlier position on specimens. Coefficient of Correlation (CC) thus found as 99.99% in healthy bone and 99.97% in osteoporotic bone, as calculated by expression given in Eq. 4.1.

$$\boldsymbol{CC} = \frac{\sum_{i=1}^{N}(x_i-\bar{x})(y_i-\bar{y})}{(N-1)\sigma_x\sigma_y} \tag{4.1}$$

Where, $\boldsymbol{x_i}$and $\boldsymbol{y_i}$ are the values of conductance at $\boldsymbol{i^{th}}$ frequency, $\boldsymbol{N}$ is number of data points, $\bar{\boldsymbol{x}}$ and $\bar{\boldsymbol{y}}$ are the mean of data points of two signature for comparison and $\boldsymbol{\sigma_x}$ and $\boldsymbol{\sigma_y}$ are the standard deviation of data points from mean values of two signatures.

4.3.2.3 Comparison of healthy and osteoporotic bones signatures

Fig. 4.7 shows the comparison of conductance signature of free BEMG, BEMG clamped on healthy bone and BEMG clamped on Osteoporotic bone. Due to decrease in bone mineral density of osteoporotic bone, a right shift of signatures of BEMG clamped on osteoporotic bone with respect to the signatures of BEMG clamped on healthy bone, can be clearly seen from the figure, as decrease in density of bone causes an increase in natural frequency of bone according to Eq. 3.1.

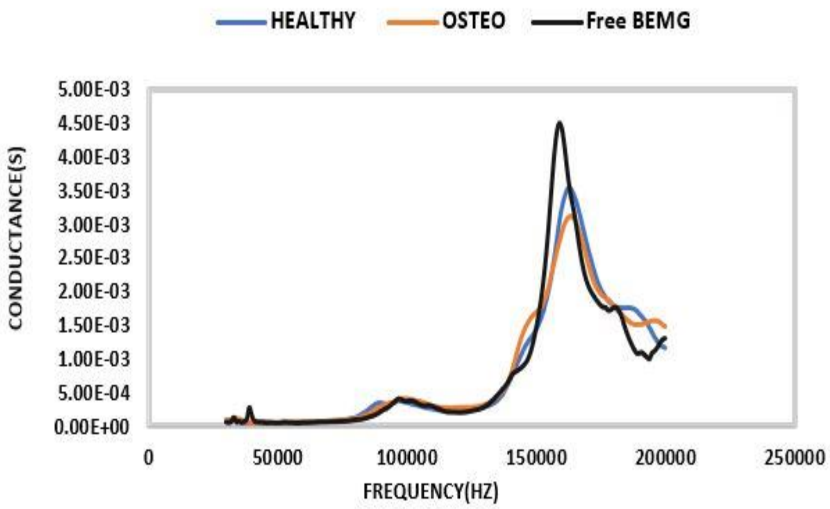


Figure 4.7: Comparison of healthy and osteoporotic bones signatures with free BEMG signature.

4.4 CONCLUDING REMARKS

This chapter has showed a simplified version of the BEMG technique based on torque wrench for attaining precise mechanical interaction between BEMG and bone specimens. Elimination of complex electrical equipments made this technique more user friendly and cost effective. Coefficient of correlation of 0.99 value gives the indication of good repeatability of signatures. Significant horizontal and vertical shifts have been found while comparing the signatures of healthy and osteoporotic bones depicting the decay in bones due to loss in its mineral density. In overall, BEMG is proved as a successful invention in field of bio-medical structure health monitoring of bones undergoing process of osteoporosis. It has strong potential to substitute the currently prevalent DEXA, which is hazardous in nature.

CHAPTER 5

VALIDATION OF EXPERIMENTAL RESULTS WITH CLINICAL TRIALS ON LIVE SUBJECTS

5.1 INTRODUCTION

In previous chapter, BEMG technique proved its successful application for monitoring health condition of human bones encompassing physiological decay or osteoporosis in lab environment. This proposed work on enhancing the tightening mechanism of BEMG has also worked wonder when it comes to paving the way on account of development of safe and low-cost technique in order to serve many underprivileges in contrast to the DEXA technique. To validate the above statement, trials on live subjects had been done by acquiring their signatures in laboratory environment through above proposed BMEG technique followed by obtaining their DEXA findings in clinics under supervision of medical expertise. Thereafter comparison of both the results in detailed manner was carried out.

5.2 LABORATORY TESTING ON LIVE SUBJECTS

After obtaining the successful results of BEMG on artificial bones, the work was been extended to test the BEMG on live subjects in controlled laboratory environment. As per required norms of institute ethical committee, A group of five army officials was tested after taking their consent to volunteer and approval of institute ethical committee as given Appendix F.

5.2.1 Experimental details

BEMG was tied at forearm of right hand as shown in Fig.5.1, of the live subjects using two tourniquets. Length and diameter of hand bone were also recorded prior to testing. The idea to replace the jubilee clamps with tourniquets was to facilitate the ease of tightening of BEMG on hands of subjects and to minimize the discomfort of subjects caused by metal-based jubilee clamps. Strain achieved on tightening of BEMG by tourniquets was equivalent to that achieved in fully clamped conditions through jubilee clamps.

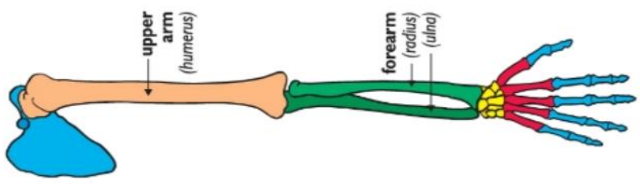
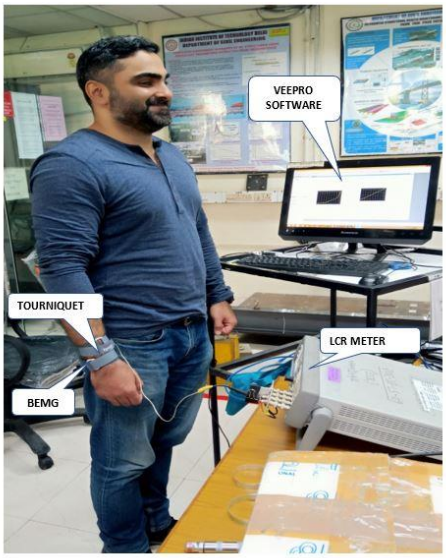
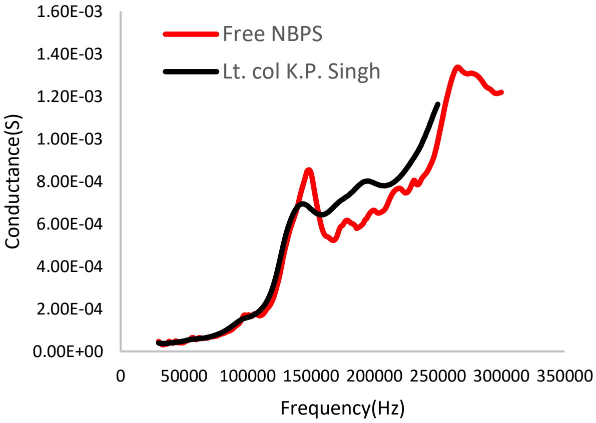


Figure 5.1: Human hand bone Anatomy

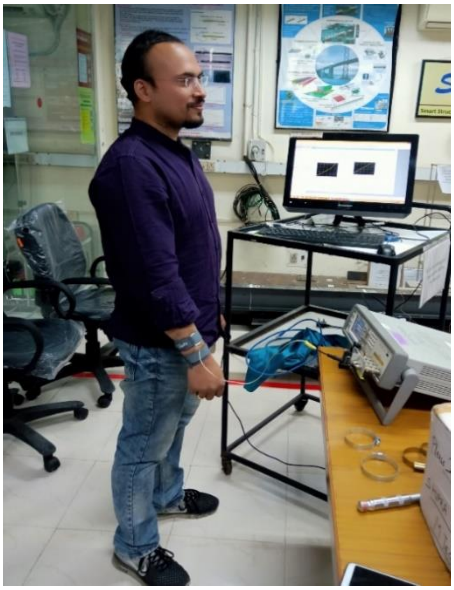
5.2.2. Observations and results

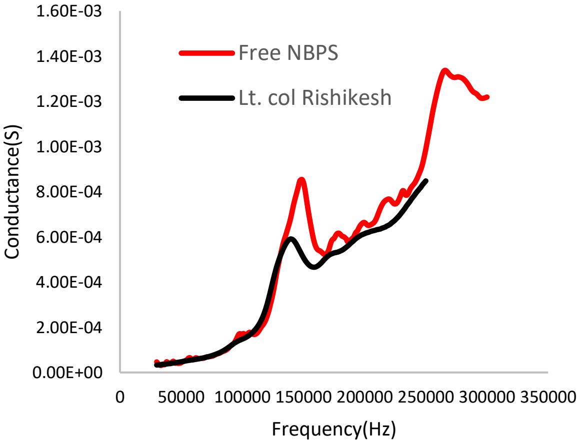
SUBJECT 1



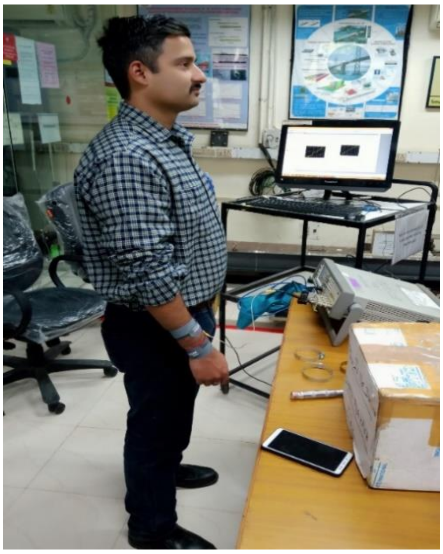


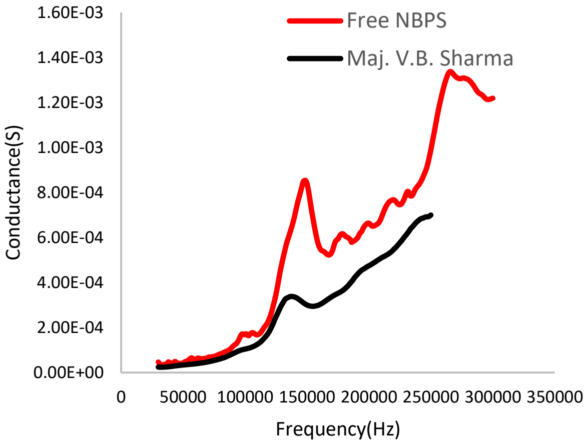
SUBJECT 2



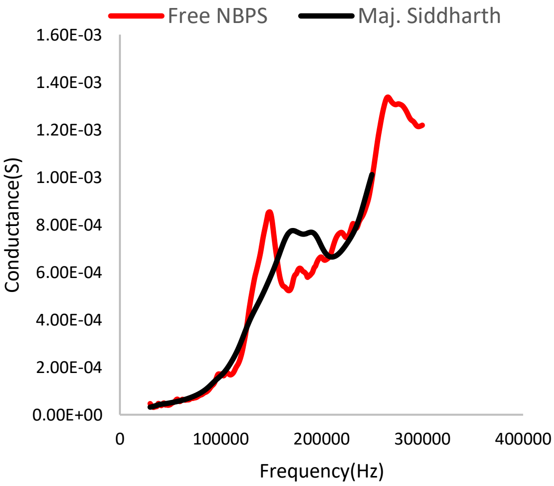


SUBJECT 3





SUBJECT 4



SUBJECT 5

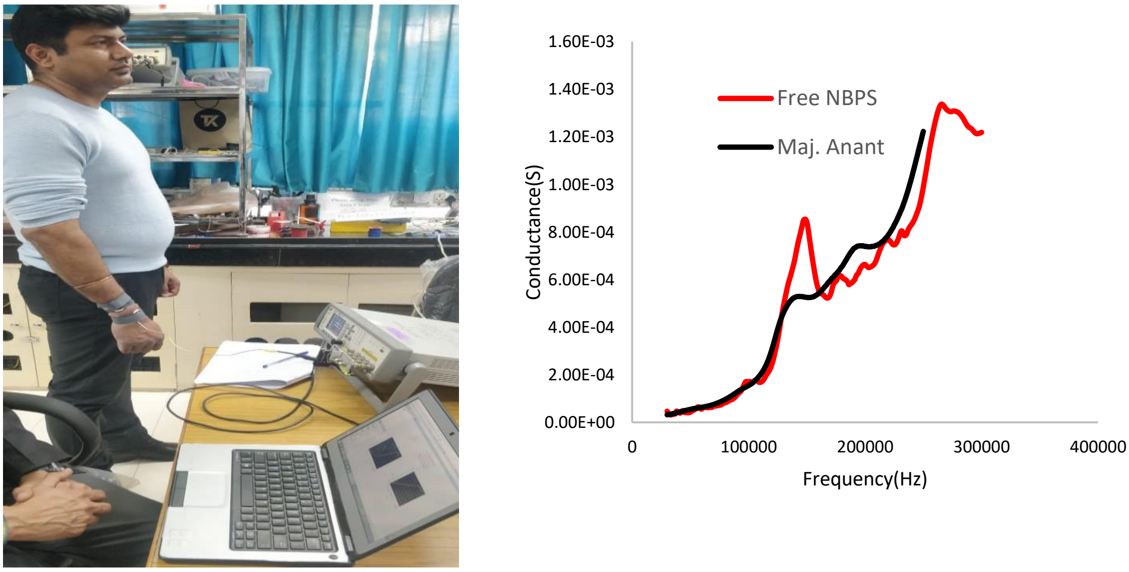


Figure 5.2: Laboratory testing and conductance signature of Subject 1 to 5

Figure 5.3: DEXA Scanning of Live Subjects at ISIC

5.3 CLINICAL TRIALS ON DEXA

The clinical testing on DEXA was been performed at Indian Spinal Injury Centre (ISIC) located at Vasant Kunj area in New Delhi, under supervision of medical expertise in area of Orthopaedics. Right hand of the subjects was placed under DEXA for scanning as same bone was used in case of BEMG testing, as shown in Fig.5.3. Details of Test results can be seen from Appendix D. and DEXA results is briefly tabulated in table 5.1 below.

Table 5.1 ***BEMG and DEXA results of live subjects***

SUBJECTS	NAMES	BONE MINERAL DENSITY (g/cm^2)	T-SCORE
1	Lt. Col. K.P. Singh	0.992	-0.8
2	Lt. Col Rishikesh S.	1.004	0.0
3	Major V.B. Sharma	0.907	-0.9
4	Major S.S. Tanwar	0.973	-0.3
5	Major. Anant Bahl	0.945	-0.6

5.4 VALIDATION OF LABORATORY RESULTS WITH DEXA RESULTS

5.4.1 Impedance extraction from current admittance signatures of live subjects

The analysis of conductance signatures acquired using the BEMG is one step further by employing extracted mechanical impedance rather than the raw conductance signatures for diagnostics of bones. This is done by utilizing the computational procedure by Bhalla et al. (2017). It is well established that the extracted structural effective drive point (EDP) impedance carries vital information about the dynamic characteristics of the host structure, here the bones of live subjects. Hence, the EDP based identification is employed in evaluating the diagnostic condition of bone. Chapter 2 and Appendix B outlines the theoretical and the computational procedure to extract the mechanical impedance of the host structure from admittance signatures acquired through PZT patch respectively. Fig. 2.4 shows the analogy between electrical impedance (LCR) and mechanical impedance of structure (SDOF).

5.4.2 Observations

A close examination of the extracted impedance components in the frequency range of 85-110 kHz, as shown in Fig 5.6, all five live subjects suggested that the system behaviour was similar to a series spring, mass and damper (k-c-m) combination as demonstrated by Bhalla et.al. (2017). Fig. 5.4 shows the typical variation of a series k-m-c system and Fig. 5.5 shows the typical variation of a parallel k-m-c system.

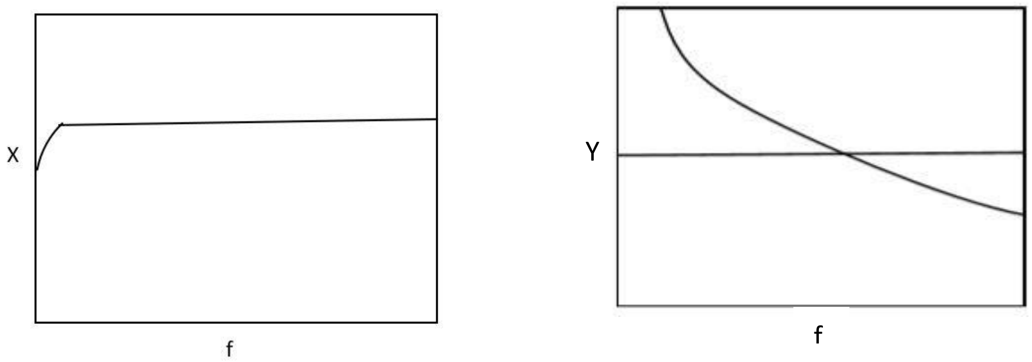


Figure 5.4: x and y for a standard series k-m-c system

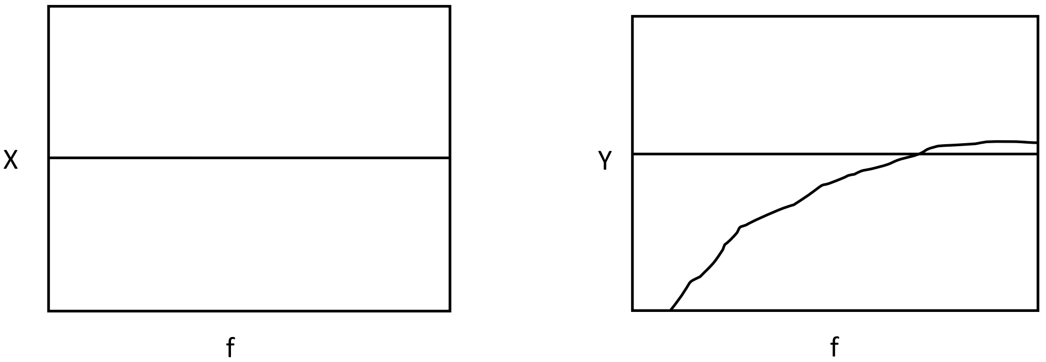
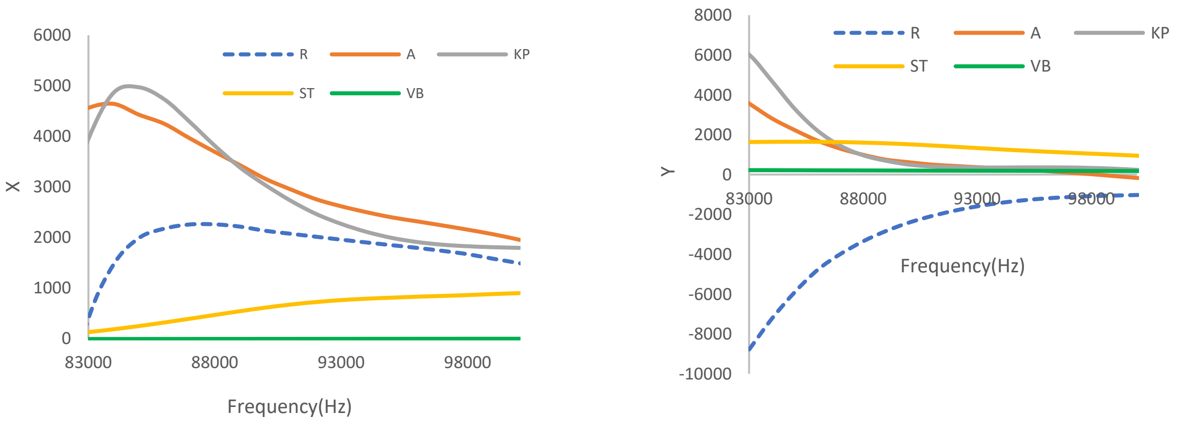
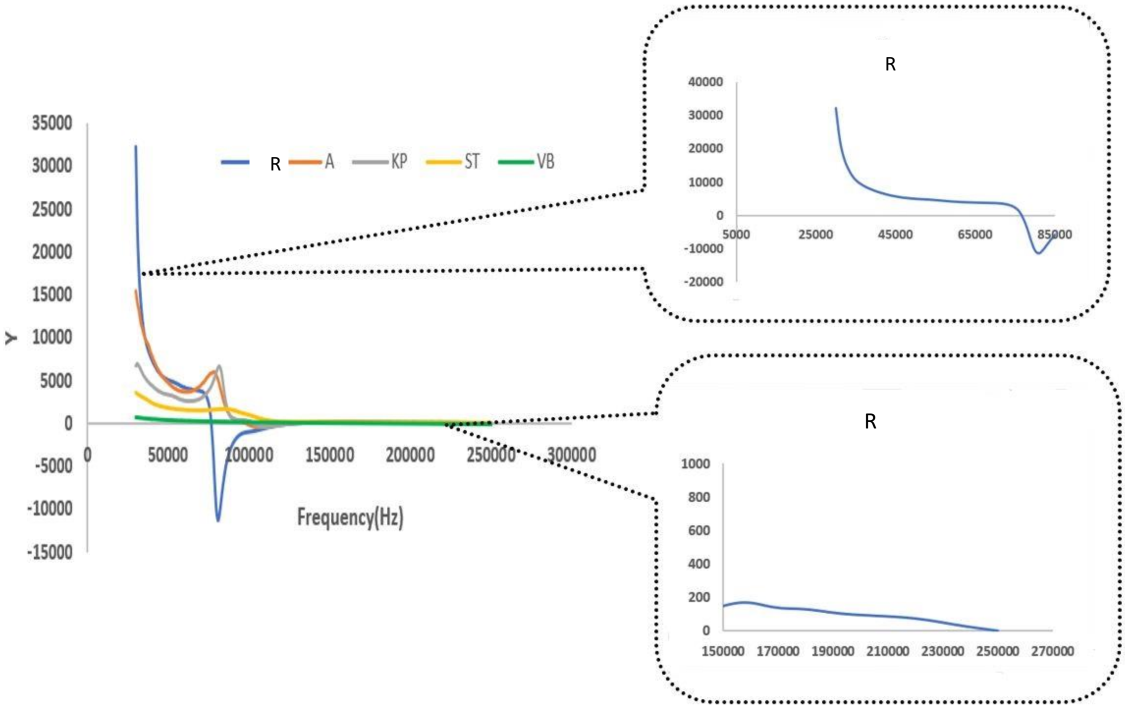


Figure 5.5: x and y for a standard parallel k-m-c system



(a)



(b)

Figure 5.6: (a) x and y for all Five subjects (**R**: Lt. Col. Rishikesh, **A**: Major Anant Bahl, **KP**: Lt. col. K.P. Singh, **ST**: Major Siddharth Tanwar, **VB**: Major V.B. Sharma), **(b)** closer view of x and y for **R**: Lt. Col. Rishikesh of x and y in different frequency ranges

From Table 5.1 it can be seen that bone mineral density and T-score of all subjects are in the same range and from Fig. 5.6 we can see that the system characteristics i.e. mechanical Impedance extracted from admittance signature through BEMG are also same for all the five subjects. Hence it can be concluded that there exists a good correlation between results of DEXA with the results extracted from BEMG using EMI technique.

5.5 CONCLUDING REMARKS

BEMG came out to be easy wearing device with minimum discomfort after replacing jubilee clamps with tourniquets. Difference between conductance signatures of live subjects and conductance signature of free BEMG can be clearly seen from Fig 5.2. Also, DEXA results i.e. Bone Mineral Density and T-Score were also found in similar range of 0.907-1.004 g/cm^2 and -0.9 to 0.0 respectively. According to the standard results of DEXA scanning all five subjects comes under healthy category. Also, all the live subjects are showing similar mechanical system, extracted from structural impedance approach, and hence BEMG giving satisfactorily results when compared with DEXA results. This is the first time that the equivalent impedance-based analysis has been employed to identify a mathematical system for a bone that identified to be healthy by DEXA scanning.

CHAPTER 6

CONCLUSIONS AND FUTURE RECOMMENDATIONS

This chapter consolidates the findings of research undertaken, i.e. enhancement and evaluation of non-bonded piezo sensors in bio-medical structural health monitoring. Also, some of the limitations have been listed out in this chapter followed by future recommendations.

6.1 CONCLUSIONS

Based on the experiments conducted and observations found in this research so far, the following conclusions can be derived as:

1. A new improved clamping technique is proposed and validated which is quite simple in execution as it does not involve ESGs and DMM.
2. Experimental frequencies correlates satisfactorily with theoretical frequencies. Structural frequencies are more prominent in range of 60 kHz to 145 kHz for both healthy and osteoporotic bone.
3. BEMG technique based on torque wrench for attaining precise mechanical interaction between BEMG and bone specimens showed good results. Also, elimination of complex electrical equipments made this technique more user friendly and cost effective. It has strong potential to substitute the currently prevalent DEXA, which is hazardous in nature.
4. BEMG facilitated the testing with greater ease on live subjects. It is validated that the healthy subjects exhibit series k-m-c system.

6.2 LIMITATIONS

Some limitations found regarding this research are listed as follows:

1. Owing to the present material i.e. Polyvinyl chloride, DEXA of artificial specimens could not be performed.
2. Bone peaks have found mixed with NBPS peaks.
3. Wrist band NBPS is less effective in giving prominent peaks.
4. Torque wrench-based technique could not be used on live subjects.
5. Sample size for DEXA scanning was considered small.

6.3 FUTURE RECOMMENDATIONS

Based on the limitations of this research, following work has recommended for further in this project:

1. Artificial specimens made from DEXA compatible material may be looked for so that experimental results of bone specimens should be validated against clinical findings Before coming to live subjects.
2. Peaks identification may be elaborated more in order to find clear structural peaks which are not coinciding with NBPS peaks.
3. Numerical investigation, by developing a numerical model of NBPS and host structure, can be incorporated along with the experimental part.
4. Experiments on easily accessible body parts like tibia, rib cages can be conducted for getting closer to a wearable device for detecting osteoporosis in these body parts.
5. Also, the Osteoporotic group needs to be included for testing in both laboratory and clinic.
6. More number of live subjects testing are required in order to validate BEMG Laboratory results against clinical results to claim the substitution of BEMG technique over DEXA technique.

AUTHOR'S PUBLICATIONS

1. Shipra Prakash, Shashank Srivastava, Suresh Bhalla, "Evaluation of bone Electro-Mechano Gram (EMG) as a low-cost substitution of DEXA for osteoporosis detection," *Proc. SPIE 11381, Health Monitoring of Structural and Biological Systems* IX, 113812Q (27 April 2020); doi: 10.1117/12.2572558, 27 April 2020 - 1 May 2020, Online Only, California, United States

APPENDIX A

Theoretical Frequencies calculated using empirical relation given in equation 3.1 (Chopra, 1995)

n	(2n-1)	axial freq. (H)	axial freq. (O)
1	1	2.80917	2950.89
2	3	8427.51	8852.67
3	5	14045.85	14754.45
4	7	19664.19	20656.23
5	9	25282.53	26558.01
6	11	30900.87	32459.79
7	13	36519.21	38361.57
8	15	42137.55	44263.35
9	17	47755.89	50165.13
10	19	53374.23	56066.91
11	21	58992.57	61968.69
12	23	64610.91	67870.47
13	25	70229.25	73772.25
14	27	75847.59	79674.03
15	29	81465.93	85575.81
16	31	87084.27	91477.59
17	33	92702.61	97379.37
18	35	98320.95	103281.15
19	37	103939.29	109182.93
20	39	109557.63	115084.71
21	41	115175.97	120986.49
22	43	120794.31	126888.27
23	45	126412.65	132790.05
24	47	132030.99	138691.83
25	49	137649.33	144593.61
26	51	143267.67	150495.39
27	53	148886.01	156397.17
28	55	154504.35	162298.95
29	57	160122.69	168200.73
30	59	165741.03	174102.51

APPENDIX - B

EXTRACTION OF STRUCTURAL MECHANICAL IMPEDANCE FROM ADMITTANCE SIGNATURES (Bhalla and Soh, 2004)

The electro-mechanical admittance consists of two parts, active and passive, given as:

$$\bar{Y} = \overline{Y_P} + \overline{Y_A} = 4\omega j \frac{l^2}{h}\left(\overline{\varepsilon_{33}^T} - \frac{2d_{31}^2\overline{Y^E}}{1-\nu}\right) + \frac{8\omega d_{31}^2\overline{Y^E}l^2}{h(1-\nu)}\left(\frac{Z_{a,eff}}{Z_{s,eff}+Z_{a,eff}}\right)\overline{T_l} \quad \text{(A.1)}$$

The passive part of the admittance, $\overline{Y_P}$ solely depends upon the PZT properties while the active part of the admittance, $\overline{Y_A}$ is dependent both on the PZT properties as well as the mechanical impedance of the host structure. The passive component of the admittance signature can be further divided into imaginary and real parts by expanding,

$$\overline{\varepsilon_{33}^T} = \varepsilon_{33}^T(1-\delta j)\,;\ \overline{Y^E} = Y^E(1+\eta j) \quad \text{(A.2)}$$

where, η and δ are the mechanical loss factor and dielectric loss factor respectively. Putting the values of $\overline{\varepsilon_{33}^T}$ and $\overline{Y^E}$ from equation A.2 into equation A.1, $\overline{Y_P}$ becomes:

$$\overline{Y_P} = G_P + jB_P = \frac{4\omega l^2}{h}(\delta\varepsilon_{33}^T + K\eta) + j\frac{4\omega l^2}{h}(\varepsilon_{33}^T - K); K = \frac{2d_{31}^2\overline{Y^E}}{1-\nu} \quad \text{(A.3)}$$

G_p and B_p can be calculated using the free-free condition of PZT patch before bonding. Deducting the PZT's contribution from the admittance signature:

$$\overline{Y_A} = \bar{Y} - \overline{Y_P} = G_A + jB_A \quad \text{(A.4)}$$

Substituting, $\overline{Y^E} = Y^E(1+\eta j)$ and $\bar{T} = r + jt$ in the expression of $\overline{Y_A}$ in equation A.1 and rearranging the terms and comparing with equation A.4:

$$M + jN = \left(\frac{Z_{a,eff}}{Z_{s,eff}+Z_{a,eff}}\right)(R + jS) \quad \text{(A.5}$$

$$M = \frac{B_A h}{4\omega K l^2}; N = -\frac{G_A h}{4\omega K l^2};\ R = r - j\eta; S = t + j\eta \quad \text{(A.6)}$$

Further expanding $Z_{s,eff} = x + jy$; $Z_{a,eff} = x_a + jy_a$, the real and imaginary components of the structural impedance are obtained as:

$$x = \frac{M(x_aR - y_aS) + N(x_aS + y_aR)}{M^2+N^2} - x_a;\ y = \frac{M(x_aS + y_aR) - N(x_aR - y_aS)}{M^2+N^2} - y_a \quad \text{(A.7)}$$

APPENDIX - C

MATLAB PROGRAM TO COMPUTE STRUCTURAL IMPEDANCE (*x*, *y*) FROM THE ADMITTANCE SIGNATURE (Bhalla, 2004)

```
close all;
clc;
%impedancep1.m (single peak case)
%MATLAB program to obtain structural impedance from PZT experimental signatures.
%based on updated PZT model
%program is based on the new 2D model based on effective impedance.
%PZT parameters- based on measurement.

%Inputs file: frequency (kHz), G (S), B (S)
data = xlsread('CVS_S_1st.xls'); %Data-matrix, stores the experimental signatures

%Parameters of S2002-6
LA=0.005; HA= 0.0002; RHO=7800; D31= -2.1e-10;mu=0.3;
Y11E= 6.67e10; E33T=1.7328e-8; ETA= 0.03; DELTA= 0.0225;
cf = 0.885;

f = data(:,1);          %Frequency in Hz
G = data(:,2);          %Conductance in S
B = data(:,3);          %Susceptance in S
%K = 2*D31*D31*Y11E / (1-mu);
K = 4.63e-9;
no=size(f);

for I = 1:no,

%Calculation of active signatures
omega(I) = 2*pi*f(I);
multi(I) = 4*(LA * LA * omega(I)) / HA;
Gp(I) = multi(I) * (E33T * DELTA + K * ETA);

GA(I) = G(I)- Gp(I);
Bp(I) = multi(I) * (E33T - K);
BA(I) = B(I) - Bp(I);

%Calculation of M and N
M(I) = (BA(I)*HA)/(4*omega(I)*K*LA*LA);
N(I) = (-GA(I)*HA)/(4*omega(I)*K*LA*LA);

%Calculation of wave number
cons = (RHO * (1-mu*mu)/ (Y11E * (1 + ETA * ETA)))^0.5;
k_real(I) = cons * omega(I);
k_imag(I) = cons * omega(I) * (-0.5 * ETA);
```

```
rl(I) = k_real(I) * LA * cf;
im(I) = k_imag(I) * LA * cf;

%Calculation of tan(kl)/kl
 a(I) = (exp(-im(I)) + exp(im(I))) * sin(rl(I));
b(I) = (exp(-im(I)) - exp(im(I))) * cos(rl(I));
c(I) = (exp(-im(I)) + exp(im(I))) * cos(rl(I));
d(I) = (exp(-im(I)) - exp(im(I))) * sin(rl(I));
u(I) = c(I) * rl(I) - d(I) * im(I);
v(I) = d(I) * rl(I) + c(I) * im(I);
h(I) = u(I)^2 + v(I)^2;
r(I) = (a(I) * u(I) - b(I) * v(I)) / h(I);
t(I) = (-1.0) * (a(I) * v(I) + b(I) * u(I)) / h(I);

%Calculation of actuator impedance
multia(I) = (HA * Y11E) / (pi * (1-mu)* f(I));
Big_rt(I) = r(I) * r(I) + t(I) * t(I);
xa(I) = multia(I) * (ETA * r(I) - t(I)) / Big_rt(I);
ya(I) = multia(I) * (-1.0) * (r(I) + ETA * t(I)) / Big_rt(I);



%Calculation of structural impedance
R(I) = r(I) - ETA * t(I);
S(I) = ETA * r(I) + t(I);
P(I) = xa(I) * R(I) - ya(I) * S(I);
Q(I) = xa(I) * S(I) + ya(I) * R(I);
MN(I)= M(I)^2+N(I)^2;
x(I) = (P(I)*M(I)+Q(I)*N(I))/MN(I) - xa(I);
y(I) = (Q(I)*M(I)-P(I)*N(I))/MN(I) - ya(I);
Z(I)=(x(I)^2+y(I)^2)^0.5;
Za(I)=(xa(I)^2+ya(I)^2)^0.5;
phase(I)=180*atan(y(I)/x(I))/pi;        %Angle in degrees
end
x=x; y=y;
output = [f x y];
xlswrite('Impedance_CVS_S_1st.xls',output);
```

APPENDIX – D

DETAILED DEXA REPOTRS OF LIVE SUBJECTS

INDIAN SPINAL INJURIES CENTRE
SECTOR-C, VASANT KUNJ
NEW DELHI-110070
PHONE:91-11-4225 52225

Bone Densitometry Report: Monday, March 16, 2020

Referring Physician: DR BHALLA

PATIENT:

Name:	SINGH, KANWAR PREET				
Patient ID:	EMINBPS	**Birth Date:**	03-10-84	**Height:**	182.0 cm
Sex:	Male	**Measured:**	16-03-20	**Weight:**	93.0 kg
Indications:		**Fractures:**		**Treatments:**	

ASSESSMENT:

The BMD measured at Forearm Radius 33% is 0.922 g/cm² with a T-score of -0.8 is normal.

Site	Region	Measured Date	Measured Age	WHO Classification	YA T-score	BMD
Right Forearm	Radius 33%	16-03-20	35.4	N/A	-0.8	0.922 g/cm²

World Health Organization (WHO) criteria for post-menopausal, Caucasian Women:
Normal T-score at or above -1 SD
Low Bone Mass T-score between -1 and -2.5 SD
Osteoporosis T-score at or below -2.5 SD

RECOMMENDATION:

Mild to aggressive therapies are available in the form of Hormone replacement therapy (HRT), bisphosphonates, Calcitonin, and SERMs. Additionally, all patients should ensure an adequate intake of dietary calcium (1200 mg/d) and vitamin D (400-800 IU daily).

FOLLOW-UP:

People with diagnosed cases of osteoporosis or osteopenia should be regularly tested for bone mineral density. For patients eligible for Medicare, routine testing is allowed once every 2 years. The testing frequency can be increased to one year for patients who have rapidly progressing disease, or for those who are receiving medical therapy to restore bone mass.

Based on these results, a follow-up exam is recommended in March 2022

(not specified)

INDIAN SPINAL INJURIES CENTRE
SECTOR-C, VASANT KUNJ
NEW DELHI-110070
PHONE:91-11-4225 52225

Bone Densitometry Report: Monday, March 16, 2020

Referring Physician: DR BHALLA

PATIENT:

Name:	SHAHI, RISHIKESH				
Patient ID:	EMINBPS	**Birth Date:**	12-10-84	**Height:**	172.0 cm
Sex:	Male	**Measured:**	16-03-20	**Weight:**	73.0 kg
Indications:		**Fractures:**		**Treatments:**	

ASSESSMENT:

The BMD measured at Forearm Radius 33% is 1.004 g/cm² with a T-score of 0.0 is normal.

Site	Region	Measured Date	Measured Age	WHO Classification	YA T-score	BMD
Right Forearm	Radius 33%	16-03-20	35.4	N/A	0.0	1.004 g/cm²

World Health Organization (WHO) criteria for post-menopausal, Caucasian Women:
Normal T-score at or above -1 SD
Low Bone Mass T-score between -1 and -2.5 SD
Osteoporosis T-score at or below -2.5 SD

RECOMMENDATION:

Mild to aggressive therapies are available in the form of Hormone replacement therapy (HRT), bisphosphonates, Calcitonin, and SERMs. Additionally, all patients should ensure an adequate intake of dietary calcium (1200 mg/d) and vitamin D (400-800 IU daily).

FOLLOW-UP:

People with diagnosed cases of osteoporosis or osteopenia should be regularly tested for bone mineral density. For patients eligible for Medicare, routine testing is allowed once every 2 years. The testing frequency can be increased to one year for patients who have rapidly progressing disease, or for those who are receiving medical therapy to restore bone mass.

Based on these results, a follow-up exam is recommended in March 2022

INDIAN SPINAL INJURIES CENTRE
SECTOR-C, VASANT KUNJ
NEW DELHI-110070
PHONE:91-11-4225 52225

Bone Densitometry Report: Monday, March 16, 2020

Referring Physician: DR BHALLA

PATIENT:

Name:	SHARMA, V B				
Patient ID:	EMINBPS	**Birth Date:**	08-02-86	**Height:**	173.0 cm
Sex:	Male	**Measured:**	16-03-20	**Weight:**	72.0 kg
Indications:		**Fractures:**		**Treatments:**	

ASSESSMENT:

The BMD measured at Forearm Radius 33% is 0.907 g/cm² with a T-score of -0.9 is normal.

Site	Region	Measured Date	Measured Age	WHO Classification	YA T-score	BMD
Right Forearm	Radius 33%	16-03-20	34.1	N/A	-0.9	0.907 g/cm²

World Health Organization (WHO) criteria for post-menopausal, Caucasian Women:
Normal: T-score at or above -1 SD
Low Bone Mass: T-score between -1 and -2.5 SD
Osteoporosis: T-score at or below -2.5 SD

RECOMMENDATION:

Mild to aggressive therapies are available in the form of Hormone replacement therapy (HRT), bisphosphonates, Calcitonin, and SERMs. Additionally, all patients should ensure an adequate intake of dietary calcium (1200 mg/d) and vitamin D (400-800 IU daily).

FOLLOW-UP:

People with diagnosed cases of osteoporosis or osteopenia should be regularly tested for bone mineral density. For patients eligible for Medicare, routine testing is allowed once every 2 years. The testing frequency can be increased to one year for patients who have rapidly progressing disease, or for those who are receiving medical therapy to restore bone mass.

Based on these results, a follow-up exam is recommended in March 2022

INDIAN SPINAL INJURIES CENTRE
SECTOR-C, VASANT KUNJ
NEW DELHI-110070
PHONE:91-11-4225 52225

Bone Densitometry Report: Monday, March 16, 2020

Referring Physician: DR BHALLA

PATIENT:

Name:	TANWAR, SIDDHARTH				
Patient ID:	EMINBPS	**Birth Date:**	17-02-85	**Height:**	192.0 cm
Sex:	Male	**Measured:**	16-03-20	**Weight:**	88.0 kg
Indications:		**Fractures:**		**Treatments:**	

ASSESSMENT:

The BMD measured at Forearm Radius 33% is 0.973 g/cm² with a T-score of -0.3 is normal.

Site	Region	Measured Date	Measured Age	WHO Classification	YA T-score	BMD
Right Forearm	Radius 33%	16-03-20	35.0	N/A	-0.3	0.973 g/cm²

World Health Organization (WHO) criteria for post-menopausal, Caucasian Women:
Normal T-score at or above -1 SD
Low Bone Mass T-score between -1 and -2.5 SD
Osteoporosis T-score at or below -2.5 SD

RECOMMENDATION:

Mild to aggressive therapies are available in the form of Hormone replacement therapy (HRT), bisphosphonates, Calcitonin, and SERMs. Additionally, all patients should ensure an adequate intake of dietary calcium (1200 mg/d) and vitamin D (400-800 IU daily).

FOLLOW-UP:

People with diagnosed cases of osteoporosis or osteopenia should be regularly tested for bone mineral density. For patients eligible for Medicare, routine testing is allowed once every 2 years. The testing frequency can be increased to one year for patients who have rapidly progressing disease, or for those who are receiving medical therapy to restore bone mass.

Based on these results, a follow-up exam is recommended in March 2022

INDIAN SPINAL INJURIES CENTRE
SECTOR-C, VASANT KUNJ
NEW DELHI-110070
PHONE:91-11-4225 52225

Bone Densitometry Report: Monday, March 16, 2020

Referring Physician: DR BHALLA

PATIENT:

Name:	BAHL, ANANT				
Patient ID:	EMINBPS	**Birth Date:**	01-08-85	**Height:**	188.0 cm
Sex:	Male	**Measured:**	16-03-20	**Weight:**	97.0 kg
Indications:		**Fractures:**		**Treatments:**	

ASSESSMENT:

The BMD measured at Forearm Radius 33% is 0.945 g/cm² with a T-score of -0.6 is normal.

Site	Region	Measured Date	Measured Age	WHO Classification	YA T-score	BMD
Right Forearm	Radius 33%	16-03-20	34.6	N/A	-0.6	0.945 g/cm²

World Health Organization (WHO) criteria for post-menopausal, Caucasian Women:
Normal T-score at or above -1 SD
Low Bone Mass T-score between -1 and -2.5 SD
Osteoporosis T-score at or below -2.5 SD

RECOMMENDATION:

Mild to aggressive therapies are available in the form of Hormone replacement therapy (HRT), bisphosphonates, Calcitonin, and SERMs. Additionally, all patients should ensure an adequate intake of dietary calcium (1200 mg/d) and vitamin D (400-800 IU daily).

FOLLOW-UP:

People with diagnosed cases of osteoporosis or osteopenia should be regularly tested for bone mineral density. For patients eligible for Medicare, routine testing is allowed once every 2 years. The testing frequency can be increased to one year for patients who have rapidly progressing disease, or for those who are receiving medical therapy to restore bone mass.

Based on these results, a follow-up exam is recommended in March 2022

APPENDIX – E

CONFERENCE PAPER

Evaluation of Bone Electro-Mechano Gram (BEMG) as a Low-Cost Substitution of DEXA for Osteoporosis Detection

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ABSTRACT

For development of advanced low-cost techniques for health monitoring of biosystem to serve the mankind in holistic manner, extensive research is being carried out across the world to deploy smart materials like piezo sensors those are light weight, portable and less expensive. One such application is the non-bonded piezo sensor (NBPS) configuration based on the electro-mechanical impedance (EMI) technique addressed as bone electro-mechano gram (BEMG) in this paper for the purpose of detecting osteoporotic condition in bones. This technique is proposed to substitute currently available dual energy x-ray absorptiometry (DEXA), which is based on X-rays, whose radiation can cause harmful effects to human being. Using artificial human bones, this paper presents the experimental work done for achieving better mechanical interaction between the BEMG and the bone, resulting in improved efficacy of the configuration. In earlier research work, electrical strain gauges (ESG) and digital multimeter (DMM) were employed to establish maximum tightening and better contact to acquire the repeatability of conductance signatures, whereas in this paper the use of more expedient torque wrench (2.5-11 Nm) based tightening has been demonstrated for effective tightening and attainment of good repeatability of the conductance signature. BEMG is performed on two bones, one representing healthy bone and other the osteoporotic bone, by employing jubilee clamps and torque wrench. A high value of Coefficient of correlation equal to 0.99 is obtained between any two signature in healthy state, thus demonstrating excellent repeatability of signatures. The conductance signatures acquired depict significant difference between healthy and osteoporotic bone conditions. This tightening method was found user friendly, cost effective and eliminating the use of complex electrical equipments.

Keywords: Bio-medical engineering, bio-medical structural health monitoring (BSHM), lead zirconate titanate (PZT), Non-bonded piezo sensor (NBPS), Directly bonded piezo sensor (DBPS), bone, osteoporosis, electro-mechanical impedance (EMI) technique, Bone electro-mechano gram (BEMG), Dual energy x-ray absorptiometry (DEXA).

1. INTRODUCTION

Currently available dual-energy x-ray absorptiometry (DEXA) technique, being widely used for measuring bone mineral density and detecting osteoporosis disease in bones, has a working principle based on X-ray technique. X-ray involves exposure of human beings to high dose of radiation that can cause damage to tissue, for example, skin burns and eye lens cataract. Blurring of image owing to inadvertent movement of subject is also very common. Besides this, soft tissue organs with abnormalities are of unknown and irregular shape, thus making them difficult to be recognized. Also, DEXA has proven as an expensive technique to many underprivileged people in developing countries like India. Hence, in view of development of low-cost techniques, extension of SHM technologies to the health monitoring of biosystem have been gaining significant attention for research efforts worldwide. Human skeleton, a supporting framework, exhibits structural properties e.g. Mass, Stiffness, Damping, Modulus of elasticity, poisons ratio etc. making it suitable for detection of physiological damage/deformities employing EMI technique using PZT patches[4] which are light weight, portable and less expensive. In current state-of-art, DBPS and NBPS configurations[6] have been employed to serve the purpose of detecting osteoporosis in human bones experimenting on artificial Bones made up of Polyvinyl chloride (PVC). NBPS configuration is successfully adopted as a non-invasive technique, referred as Bone Electro-Mechano Gram (BEMG) hence paving the way of path ahead for development of easily available and affordable device for detecting ailments in human bones. The proposed work shows the mechanism for achieving better mechanical interaction between the BEMG and artificial human bones by using torque wrench as an improvement to earlier research work where electrical strain gauge and digital multimeter were employed to establish maximum tightening to acquire the repeatability of conductance signatures. This paper discusses the EMI technique in brief followed by evaluation of BEMG, details of experiments, their results and its futuristic applications.

2. ELECTRO-MECHANICAL IMPEDANCE (EMI) TECHNIQUE

The electro-mechanical impedance technique[1] employs the PZT patch both as actuator and sensor simultaneously for SHM. This technique involves bonding a PZT patch with a thin layer of high strength epoxy adhesive, electrically excited by means of a LCR meter or an impedance analyzer over a frequency range of 30-400 kHz in sweep mode[2] to extract structural dynamic behavior in form of characteristic admittance signature of the structure (consisting of real part, *conductance* and imaginary part , *susceptance*) to be altered only by a physical change in the structure such as damage. At any future point of time, whenever the condition of the structure is to be assessed, the signature is acquired again and compared with the baseline signature. Consistency of the signature indicates the wellbeing of the structure[2,3]. Bhalla and Suresh[7] has successfully demonstrated the application of the EMI technique for monitoring condition of bones using PZT in bonded configuration.

3. EVALUATION OF BONE ELECTRO-MECHANO GRAM (BEMG)

Extension of EMI technique employing PZT in directly bonded configuration[4] for the assessment of bone health condition has its own limitations as the process involves bonding of PZT onto the surface thereby making it unsuitable for the testing on live human subjects. To overcome these limitations, Srivastava and Bhalla[6] demonstrated the development of NBPS configuration for assessment of physiological decay and damage in human bones. The major challenge in implementing the NBPS configuration, however, is to ensure adequate transmission of forces between the piezo patch and the host structure maintaining the PZT patch in the non-bonded mode, while at the same time ensuring repeatability of the signatures. To serve this purpose, the current state-of-art of the technique demonstrated by Srivastava and Bhalla[5] proposed the mechanism of tightening of NBPS by using two jubilee clamps through screw followed by measuring strain to quantify the strain achieved in clamps for maximum tightening using electrical strain gauges and digital multimeter. Involvement of complex electrical equipments and usage of electricity has again proved to be cumbersome and uneconomic one. To make the technique user friendly and economically feasible, this paper demonstrates the use of easily available torque wrench (ISO 9001:2008; PVTR-100; 2.5-11 Nm) for tightening the NBPS using two similar jubilee clamps, naming the technique as Bone Electro-Mechano Gram (BEMG). The amount of torque applied for attaining maximum tightening and repeatability of signatures was started from 3 Nm onwards. After performing many laboratory experiments it was observed that applied torque of 6 Nm shows good repeatability of signatures and successfully detects the osteoporotic condition of bone by showing significant horizontal and vertical shifts of signatures with respect to the healthy bone signatures. BEMG consisted of an aluminium strip, 70×10×1mm in size, on which a PZT patch, 10×10×0.3 mm in size, conforming to grade PIC 151 (PI Ceramic, 2014) was bonded at the midpoint using two-part araldite epoxy adhesive as shown in Figure 1(a).

(a)

(b)

Figure 1: Bone EMG in (a) Free-Free condition and (b) clamped condition

4. EXPERIMENTAL DETAILS AND RESULTS

Figure 2(a) and 2(b) shows the torque wrench and artificial bone specimens of both healthy and osteoporotic bones[5] on which tests were conducted respectively. Figure 3 shows the detailed experimental setup whereinthe bone specimen is tied to a stand with a string of negligible mass and stiffness to attain free-free boundary conditions of bone. The BEMG is then attached to an LCR meter and excited at frequency range of 30-200 kHz (model E4980, Agilent Technologies, 2014) and signatures were acquired using VEE PRO 9.3 software operating on a personal computer in laboratory-controlled environment.

(a) (b)

Figure 2: (a) Torque wrench and (b) Artificial Healthy bone with BEMG and Osteoporotic bone

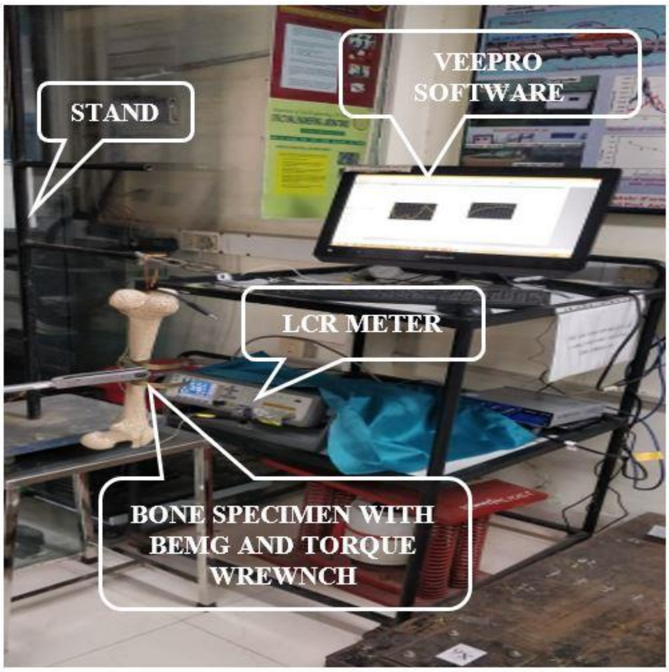

Figure 3: Experimental Setup

RESULTS

EFFECT OF DEGREE OF TORQUE APPLIED

Figure 4 and figure 5 shows the comparison of conductance signatures of BMEG at different values of torque applied in both bone specimens. A well-defined shift in signature can be seen from figure 4 and figure 5 and one can conclude that there is significant shifting of signatures while applying torque of 3 Nm to 5 Nm whereas negligible shifting of signatures was occurred while increasing the torque up to 6 Nm, showing the maximum mechanical interaction of BEMG and bones specimens at 6Nm torque.

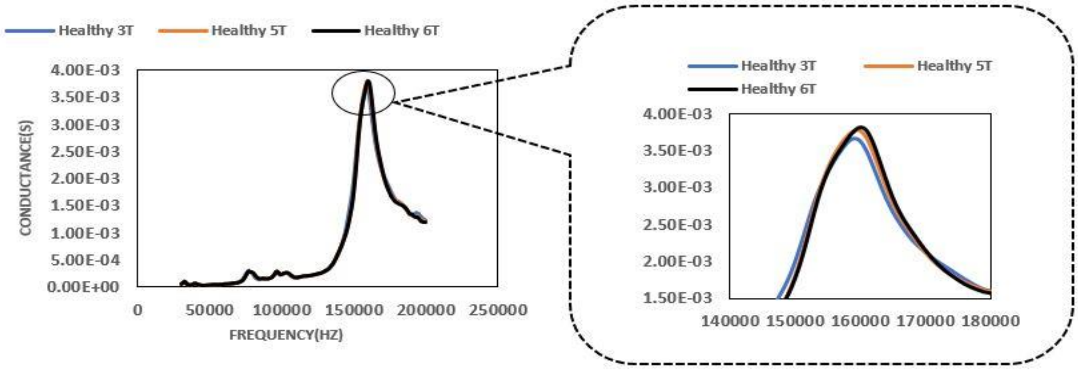

Figure 4: Conductance signature of BEMG clamped on healthy bone at 3 Nm (Healthy 3T), 5 Nm (Healthy 5T) and 6 Nm (Heathy 6T).

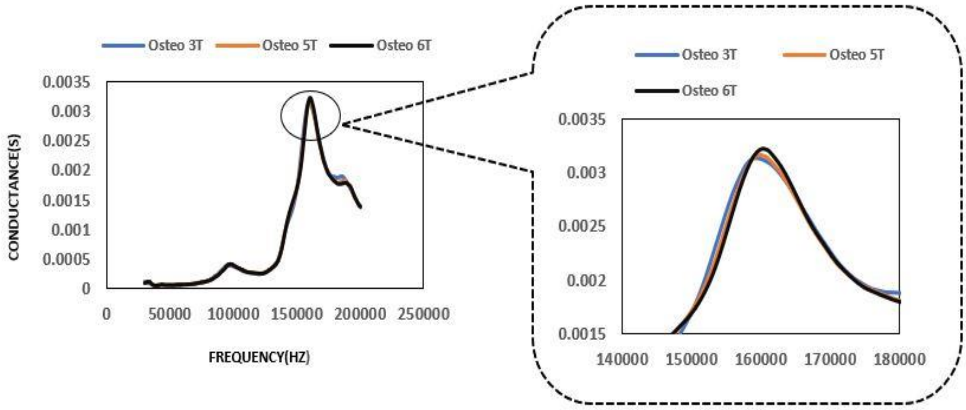

Figure 5: Conductance signature of BEMG clamped on osteoporotic bone at 3 Nm (Osteo 3T), 5 Nm (Osteo 5T) and 6 Nm (Osteo6T).

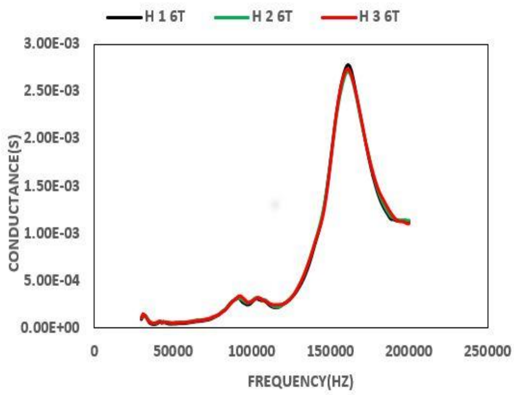

Figure 6: Repeatability of signatures in three trials of experiment at 6 Nm (6T) applied torque in Healthy bone (H1, H2 and H3)

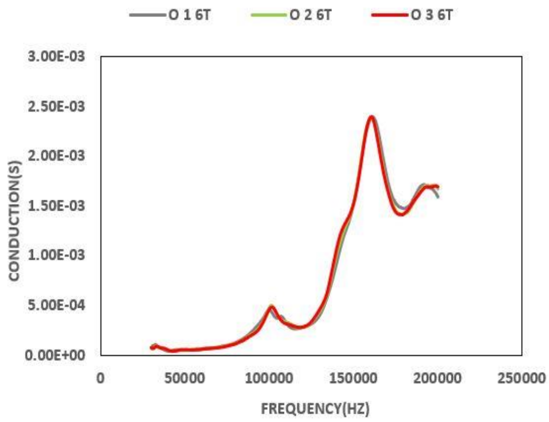

Figure 7: Repeatability of signatures in three trials of experiment at 6 Nm (6T) applied torque in Osteoporotic

bone (O1, O2 and O3)

ATTAINMENT OF REPEATABILITY

Figure 6 and figure 7 shows the repeatability of conductance signatures of healthy and osteoporotic bones respectively, subjected to 6 Nm torque when BEMG was unclamped and taken away from its position and then again clamped to its earlier position on specimens. Coefficient of Correlation (CC) thus found as 99.99% in healthy bone and 99.97% in osteoporotic bone, as calculated by expression given in equation 1.

$$\boldsymbol{CC} = \frac{\sum_{i=1}^{N}(x_i-\bar{x})(y_i-\bar{y})}{(N-1)\sigma_x\sigma_y} \quad (1)$$

Where, $\boldsymbol{x_i}$ and $\boldsymbol{y_i}$ are the values of conductance at $\boldsymbol{i^{th}}$ frequency, $\boldsymbol{N}$ is number of data points, $\bar{\boldsymbol{x}}$ and $\bar{\boldsymbol{y}}$ are the mean of data points of two signature for comparison and $\boldsymbol{\sigma_x}$ and $\boldsymbol{\sigma_y}$ are the standard deviation of data points from mean values of two signatures.

COMPARISON OF HEALTHY AND OSTEOPOROTIC BONES SIGNATURES

Figure 8 shows the comparison of conductance signature of free BEMG, BEMG clamped on healthy bone and BEMG clamped on Osteoporotic bone. Due to decrease in bone mineral density of osteoporotic bone, a right shift of signatures of BEMG clamped on osteoporotic bone with respect to the signatures of BEMG clamped on healthy bone, can be seen from the figure, as decrease in density of bone causes an increase in natural frequency of bone[6].

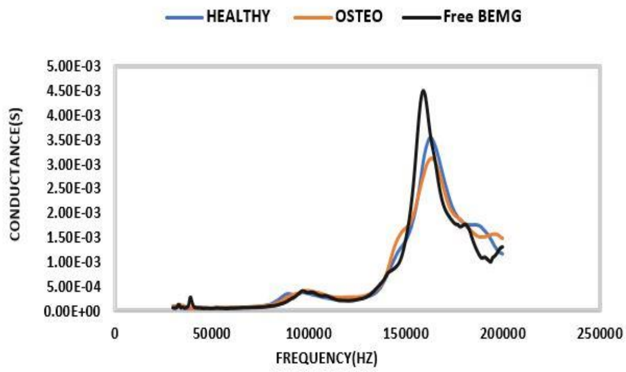

Figure 8: Comparison of healthy and osteoporotic bones signatures with free BEMG signature.

5. CONCLUSIONS

This paper has successfully demonstrated a simplified version of the BEMG technique based on torque wrench for attaining precise mechanical interaction between BEMG and bone specimens. Elimination of complex electrical equipments made this technique more user friendly and cost effective. Coefficient of correlation of 0.99 value gives the indication of good repeatability of signatures. Significant horizontal and vertical shifts have been found while comparing the signatures of healthy and osteoporotic bones depicting the decay in bones due to loss in its mineral density. In overall, BEMG is proved as a successful invention in field of bio-medical structure health monitoring of bones undergoing process of osteoporosis. It has strong potential to substitute the currently prevalent DEXA, which is hazardous in nature.

6. FUTURE WORK

BEMG shows successful application for monitoring health condition of human bones encompassing physiological decay or osteoporosis in lab environment. This proposed work on enhancing the tightening mechanism of BEMG has also worked wonder when it comes to paving the way on account of development of safe and low-cost technique in order to serve many underprivileges in contrast to the DEXA technique. To validate the above statement, trials on live subjects are under progress by acquiring their signatures through above proposed BMEG technique followed by obtaining their DEXA findings in clinics under supervision of medical expertise is being planned. Thereafter comparison of both the results in detailed manner shall be carried out.

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APPENDIX-F

SAMPLE FORMATE FOR SUBJECT INFORMATION AND CONSENT FORM

SUBJECT INFORMATION AND CONSENT FORM

M.Tech Project Title:	Evaluation and Improvement of Non-Bonded Piezo Sensor in Bio-medical Structural Health Monitoring
Student Name:	Shipra Prakash
Supervisors:	Prof. Suresh Bhalla , IIT Delhi
	Dr. Shashank Shrivastav, IGNOU Delhi
	Dr. Shakti Goel, Indian Spinal Injuries Centre Delhi

SUBJECT INFORMATION

Name:

Age:

Height:

Weight:

BMI:

I, hereby agree to be a part of this experimental program to acquire EMI signature of hand. I am healthy and do not suffer from any disease/disorder.

Signature and name: Date:

Designation and Affiliation:

To,

Chairperson

Ethical Committee for Research on Human/ Animal Subjects,

IIT DELHI

Date:

Subject: Permission letter for Research on Human/ Animal Subjects

Respected Sir,

Undersigned, a student of Institute's M.Tech Program in Structural Engineering, Department of Civil Engineering would like to conduct experiments on human subjects as a part of the M.Tech project. Consent of individuals are attached.

Permission may kindly be granted for the same.

Yours' faithfully

Supervisor:

Shipra Prakash

Entry number: 2018CES2182

ces182182@civil.iitd.ac.in

Through: Head (Civil Engg)

Submitted to : Prof. Ravi Elangovan, DBEB, Secretary

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