IMAGE RECONSTRUCTION OF UPPER LIMB BONE FRACTURES USING ELECTRICAL IMPEDANCE TOMOGRAPHY ON PYTHON FRAMEWORK

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DEDICATION

In the name of Allah, the Most Gracious and the Most Merciful.

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ABSTRACT

Minor bone fractures could occur due to traumatic incidents such as injuries, vehicle accidents, and falls. The commonly used devices to diagnose for bone fracture are X-ray, Computerized Tomography (CT)-Scan, Positron Emission Tomography (PET)-Scan, and Magnetic Resonance Imaging (MRI). For a series of post diagnosis of bone fracture, it can be health threatening to expose the patient to ionization radiation repeatedly. This research proposes to utilize Electrical Impedance Tomography (EIT) as an invasive modality to monitor the recovery of bone fracture. The aim is to develop EIT circuit to measure the electrical impedance on the phantom model of the upper limb with fractured bones using saline solution and 3D printed bones, the phantom model is reconstructed in 2D images on each cross-section layer using pyEIT and analyze the performance of the reconstructed model of fractured bone. This initiative begins with the development of the EIT circuit system, which consist of sinusoidal waveform generator 100 kHz to 10 MHz frequency range, 32-channel multiplexer unit, instrumentation amplifier with slew rate 35 V/μs, bandpass filter range of frequency from 10 kHz to 4 MHz, Root Mean Square (RMS) to Direct Current (DC) converter, 24-bit analog-to-digital converter, flexible Printed Circuit Board (PCB) 32 electrodes per layer, power supply and microcontroller. The EIT circuit is used to acquire voltage measurement using neighboring and opposite data collection techniques from the phantom tank which consist of saline solution (0.9% NaCl) and was tested on 3D printed Acrylonitrile Butadiene Styrene (ABS) bone and lamb bone. The EIT image of the phantom was reconstructed using pyEIT in three-layers slices on 3D plane. Then, the images were analyzed its performance using root mean square error (RMSE) and correlation coefficient. The RMSE value of the reconstructed images at the frequency of 400 kHz was 0.2785 ± 0.01. From the correlation coefficient between the ABS bone and lamb bone, there are significant similarity in terms of impedance between both materials with Pearson correlation with minimum values of 0.636. It would be beneficial to use the ABS material to simulate the different shape of bone fracture to be reconstructed in EIT system. The fractures are observable on several images. In addition, the depth of the bone is can also be distinguished.

ABSTRAK

Keretakan tulang kecil boleh berlaku disebabkan oleh insiden traumatik seperti kecederaan, kemalangan kenderaan dan terjatuh. Peranti yang biasa digunakan untuk mendiagnosis patah tulang ialah *X-ray*, Tomografi Berkomputer (*CT)-Scan,* Tomografi Pelepasan Positron *(PET)-Scan*, dan Pengimejan Resonans Magnetik *(MRI)*. Untuk satu siri diagnosis pasca patah tulang, boleh membahayakan nyawa untuk mendedahkan pesakit dengan sinaran pengionan berulang kali. Pada penyelidikan ini mencadangkan untuk menggunakan Tomografi Impedansi Elektrik (EIT) sebagai modaliti invasif untuk memantau pemulihan patah tulang. Matlamatnya adalah untuk membangunkan litar EIT untuk mengukur impedansi elektrik pada model buatan anggota tangan dengan tulang patah menggunakan larutan garam dan tulang cetakan 3D, model buatan telah dibina semula dalam imej 2D pada setiap lapisan keratan rentas menggunakan *pyEIT* dan menganalisis prestasi model tulang patah yang dibina semula. Inisiatif ini bermula dengan pembangunan sistem litar EIT, yang terdiri daripada penjana bentuk gelombang sinusoidal 100 *kHz* hingga 10 *MHz* julat frekuensi, unit pemultipleks 32 saluran, penguat instrumentasi dengan kadar *slew* 35 V/µs, julat penapis laluan jalur frekuensi dari 10 kHz kepada 4 MHz, penukar purata kuasa dua *(RMS)* ke arus terus (*DC)*, penukar analog-ke-digital 24-*bit*, *papan litar bercetak (PCB)* fleksibel 32 elektrod pada setiap lapisan, bekalan kuasa dan mikropengawal. Litar EIT digunakan untuk memperoleh pengukuran voltan menggunakan teknik pengumpulan data jiran dan bertentangan daripada tangki buatan yang terdiri daripada larutan garam (0.9% *NaCl*) dan telah diuji pada tulang *Acrylonitrile Butadiene Styrene (ABS)* cetakan *3D* dan tulang kambing. Imej EIT buatan telah dibina semula menggunakan *pyEIT* dalam potongan tiga lapisan pada satah 3D. Kemudian, imej dianalisis prestasinya menggunakan ralat purata kuasa dua akar (*RMSE*) dan pekali korelasi. Nilai *RMSE* bagi imej yang dibina semula pada frekuensi 400 *kHz* ialah 0.2785 ± 0.01. Daripada pekali korelasi antara tulang *ABS* dan tulang kambing, terdapat persamaan yang ketara dari segi impedans antara kedua-dua bahan dengan korelasi *Pearson* dengan nilai minimum 0.636. Adalah berfaedah untuk menggunakan bahan *ABS* untuk mensimulasikan bentuk patah tulang yang berbeza untuk dibina semula dalam sistem EIT. Patah boleh dilihat pada beberapa imej. Di samping itu, kedalaman tulang juga boleh dibezakan.

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LIST OF ABBREVIATIONS

AC	-	Alternating Current
ADC	-	Analog to Digital Converter
BIA	-	Bio-Electrical Impedance Analysis
CT	-	Computerized Tomography
DBIM	-	Distorted Born Iterative Method
DDS	-	Direct Digital Synthesis
ECF	-	Extracellular Fluid
ECM	-	Extracellular Matrix
ECG	-	Electrocardiogram
EIDORS	-	Electrical Impedance and Diffuse Optical Tomography Reconstruction Software
EIT	-	Electrical Impedance Tomography
EIM	-	Electrical Impedance Mammography
EIPG	-	Electrical Impedance Plethysmography
EIS	-	Electrical Impedance Spectroscopy
EMI	-	Electromagnetic Interference
FDA	-	Food and Drug Administration
FEM	-	Finite Element Method
GREIT	-	Graz consensus Reconstruction algorithm for EIT
IA	-	Instrumentation Amplifier
ICF	-	Intracellular Fluid
ICG	-	Electrical Impedance Cardiography
ICH	-	Intercranial Hemorrhage
MIT	-	Magnetic Induction Tomography
MMG	-	Mammography
MRI	-	Magnetic Resonance Imaging
PCB	-	Printed Circuit Board
PET	-	Positron Emission Tomography
RF	-	Radio Frequency
RMSE	-	Root Mean Square Error

SR	-	Slew Rate
VCC	-	Voltage to Current Converter
VCCS	-	Using Voltage Current Controlled Source
VCO	-	Voltage-Controlled Oscillator

LIST OF SYMBOLS

I	-	Current
V	-	Voltage
Z	-	Impedance
R	-	Resistance
X_C	-	Reactant
ρ	-	Phase Angle
L	-	Length
A	-	Area
m^2	-	Meter Square
σ	-	Conductivity Distribution
$\emptyset$	-	Electric Potential Distribution
$\hat{n}$	-	Current Injected
J	-	Conductivity Jacobian
$K(\sigma)$	-	Conductivity Matrix
z	-	Signal Measured
Z	-	FEM Of the Signal
W	-	Number Of Finite Elements in The Image
Q	-	Regularization Matrix
T	-	Tikhonov Style Regularization
$V_{measured}$	-	Vector of Physical Medium Voltage Measurements
σ_0	-	Original Context Conductivity Calculation
σ_r		Impedance Calculated
σ_c		Expected Impedance
$f(\sigma)$	-	Minimization of Error Function
R	-	Regularization Matrix
λ	-	Relaxation Vector Scalar
f_{max}	-	Maximum Frequency
i_c	-	Internal Capacitor
V_m	-	Maximum Peak Voltage of Signal
ΔV	-	Impedance Calculated from the Experimental Data

ΔV^{fem}	-	Expected Impedance from the Reconstructed FEM Model
cov	-	Covariance

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Skeleton system plays important roles in human body, such as protecting the internal organs, help maintaining the body shape and is involved in body growth. But what if this system fails to operate on its normal cause by incident that led to bone fracture? The bone fractures could occur because of traumatic incidents such as sporting injuries, vehicle accidents, falls, and conditions such as osteoporosis and some types of cancer could also easily cause bone fracture [1].

Bone plays an important role in providing strong support to the soft tissues and muscles. These bones are built up from 20% of water, 80% of it are cells, lipids, and extracellular matrix (ECM) [2]. Even though the bone structures are strong, they can still break and lead to bone fracture. In the year 2019, about 1.78 million people experienced bone fracture on the forearm [3]. Moreover, 50% of children will break a bone before adulthood. In 2010, 158 million of people who exceeded 50 years of age worldwide have a high risk of osteoporotic fracture and estimated would multiple in 2040 [4]. The most common factors causing bone fracture are traumas or specific bone diseases; bone fractures could also occur because of the micro-fracture's accumulation in healthy bones, which is called 'stress fracture'. These micro-fractures commonly occur after continuous loading [2]. There are several types of bone fractures, which can be classified into several types of fractures such as transverse, stress, oblique, greenstick and comminuted [2]. Figure 1.1 illustrated the types of fractures which occur at the femur bone.

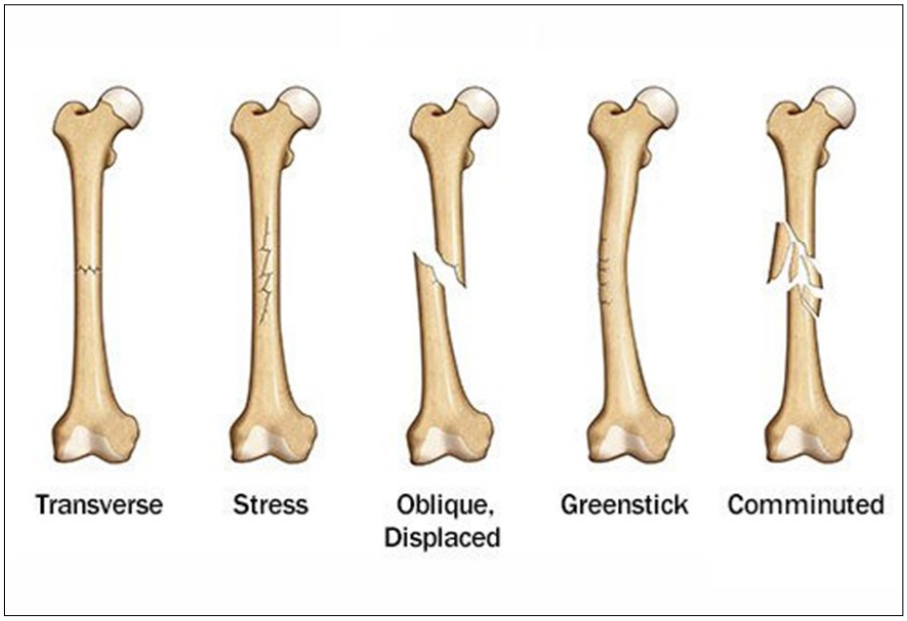

Figure 1.1 Types of Bone Fracture [2].

When bone fracture occurs, a patient will need to be diagnosed to inspect the bone's condition before and after the operation and to identify the morphology of the fracture part to determine the best treatment to be applied. There are several existing devices to perform bone imaging such as X-ray, Computerized Tomography (CT)-Scan, Positron Emission Tomography (PET)-Scan, Magnetic Resonance Imaging (MRI), Ultrasound and Electrical Impedance Tomography (EIT). In this study, will be focusing on EIT to identify the bone fracture on the upper limb.

1.2 Problem Statement

Bone healing is a natural mechanism to preserve the mechanical function of bone. This process requires cell formation and tissue remodeling [5]. Over time, this regenerative process will reform normal morphology of bone on the fracture location until the bone is completely healed. But, for the healing rate depends on bone homeostasis and several hormones in our body, which differs between each person [6]. Through the advanced imaging technology, the bone healing progress can be monitored by a physician. The common imaging devices that have been used to diagnose the bone condition such as X-rays, Computerize Tomography (CT)-Scan and Positron Emission Tomography (PET)-Scan can give good images of our internal

organs and tissues. However, overexposure of ionization radiation can lead patients to the risk of tumour, leukaemia and cancer especially to children [7]. Magnetic Resonance Imaging (MRI) is an advanced radiation-free medical device, however, is quite costly and time-consuming [8]. For monitoring the bone healing progress especially on the upper limb, it is not worth to expose the patient with radiation and high-cost device, especially for post diagnosis.

Several studies which tested EIT on bone fracture have been done, however, the number is still low and some of the studies only focus on lower limb and cranial fracture. This study aims to investigate alternative method in monitoring the condition of upper limb fracture by using EIT. To develop the circuit and the phantom model that resemble the electricity properties to the upper limb. Thus, to investigates the reconstruction images of bone fracture phantom and the most optimum range of frequency for signal measurement.

1.3 Research Objectives

The objectives of the research are:

1. To develop EIT circuit to measure the electrical impedance on the phantom model.

2. To develop phantom model of the upper limb with fractured bones using saline solution and 3D printed bones.

3. To reconstruct 2D images on each cross-section layer of the upper limb phantom using pyEIT.

4. To analyze the performance of the reconstructed model of fractured bone.

1.4 Scope of Study

This research involves the development of an upper limb phantom tank consists with saline solution and will be tested the bone fractures on the lamb bone and the ABS bone on different positions. The EIT circuit developed using Autodesk Eagle PCB consist of different compartment stack together to connect with the 16 electrodes on the EIT tank. Meanwhile, the research uses pyEIT, an open-source python package for EIT system for the image reconstruction using the Graz consensus Reconstruction algorithm for EIT (GREIT). In this research, the reconstruction only limited to the three layers, which can produce three 2D cross-sectional image on the phantom and plotted on 3D plane.

1.5 Significance of Study

This research helps to investigate an alternative method for upper limb bone condition post-diagnosis in avoiding the use of harmful radiation device to detect bone fracture. It is also used to obtain unexpensive approach in monitoring upper limb's bone fracture. It also aims to provide insights on the advantages and limitations of EIT system on bone fracture monitoring. Meanwhile, to provide enough evidence on the similarity of the reconstruction between the real bone and the ABS bone, to find an alternative method on design the phantom bone fracture for testing the reconstruction image in EIT. In addition, it aims to apply the python framework of the EIT system which is newly emerged image reconstruction tool in EIT community to test the applicability of this tool in reconstruct the EIT images.

1.6 Thesis Outline

The contents of the thesis are arranged by chapter. The contents of each chapter are as follows:

- Chapter 1 gives broad introduction of this thesis, consist of background of the study, problem statement, research objectives, scopes of study and significance of study.
- Chapter 2 presents a review on the studies related to devices used to diagnose the bone fracture. Meanwhile, discuss the fundamental and the application of the EIT such as the measurement techniques, data acquisition module, image reconstruction module and the image reconstruction algorithms.
- Chapter 3 describes the development and the experiment of the EIT system on the lamb bone and the ABS bone. This chapter discuss deeply on the circuit design, phantom design, and the reconstruction algorithms.
- Chapter 4 shows the result from the reconstructed images and discuss the outcome from the reconstruction using analytical tools. Meanwhile, address the limitation on this study.
- Chapter 5 presents the conclusion and the future recommendation to improve the limitation from this study.

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Appendix C List of Publication

Indexed Conference Proceedings

[1] A. H. Abdul Salam, Z. Nurul Farha, J. Mohd Najeb, A. Muhammad Amir, P. Jaysuman, and M. L. Hadafi Fitri. (2021) "16 by 3 Electrodes Electrical Impedance Tomography System Implementation on Cylindrical Phantom Design and Development," In *2021 IEEE-EMBS Conference on Biomedical Engineering and Sciences 2020 (IECBES2020)* (pp. 3–7). IEEE. https://doi.org/10.1109/IECBES48179.2021.9398790 **(Indexed by SCOPUS)**