Bioimpedance Measurement of Knee Injuries Using Bipolar Electrode Configuration

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Abstract—Currently, there is no suitable solution for the point-of-care diagnosis of knee injuries. A potential portable and low-cost technique for accessing and monitoring knee injuries is bioimpedance measurement. This study validated the feasibility of the bipolar electrode configuration for knee bioimpedance measurement with two electrodes placed on a fixed pair of knee acupuncture locations called Xiyan. Then, the study collected 76 valid samples to investigate the relationship between bioimpedance and knee injuries, among whom 39 patients have unilateral knee injuries, and 37 individuals have healthy knees. The self-contrast results indicated that knee injuries caused a reduction of bioimpedance of the knee by about 5% on average, which was detectable at around 100 kHz ($\approx 0.001$). Furthermore, the results analyzed by principal component analysis and support vector machines show that the detection sensitivity can reach 87.18% using the leave-one-out cross-validation. We also proposed a low-cost and portable bioimpedance measurement device that meets the needs for measuring knee joint bioimpedance.

Index Terms—Bioimpedance, bipolar electrode configuration, knee injuries, machine learning, portable device.

I. INTRODUCTION

EVERY year, approximately 720 out of 100,000 people are diagnosed with common knee injuries, including ligament tears, meniscus lesions, and others [1]. Ligament tears and menisci lesions are common injuries among those who frequently engage in vigorous physical activities [2], [3], [4], [5]. As physical exercises have gradually become a part of daily life for most people, these knee injuries are more widespread than ever before [6].

Currently, knee injuries are primarily examined with magnetic resonance imaging (MRI) [7], along with alternative methods, including X-ray, computed tomography (CT), and ultrasound scan [8], [9]. Although these imaging-based methods provide accurate information about knee conditions, expensive and large infrastructures (usually cost more than $300,000 USD) as well as professionally trained technicians are required. Clinicians also assess knee injuries by asking patients about their physical limitations and handicap conditions in some clinical practices [10], [11], [12]. However, these examination methods are not suitable for monitoring long-term rehabilitation progress or self-evaluation in the early stage. Therefore, it is an urgent demand to develop a low-cost, portable, rapid and easy-to-use assessment technology for the point-of-care of knee injuries.

Bioimpedance measurement is a promising technique that is non-invasive and can be embedded in low-cost portable devices. A portable bioimpedance measurement device usually costs less than $100 USD, and the whole measurement process can be completed in one minute [28]. The technique measures the electrical impedance of the biological tissues in a specific frequency range. In the low-frequency range ($< 1$ kHz), the injected current only flows in the extracellular fluid within biological tissues because the current cannot penetrate through the cell membrane. However, the membranes are no longer obstacles to current flow when the frequency is sufficiently high ($> 1$ MHz) [29]. Usually, the bioimpedance measured from below 1 kHz to around 1 MHz can be used to analyze the intracellular fluid and extracellular fluid, which may reflect the electrochemical changes in biological knee tissues [30]. The bioimpedance technique has been widely applied to clinical practices, such as evaluation of muscle injury severity level [31], measurement of body composition [32], [33], monitoring venous ulcers [34], and diagnosis of breast tumor [35].

Based on the literature study, we hypothesize that the physical-chemical processes and tissue changes involved in knee injuries can induce a reduction of bioimpedance. Most of disorders or injuries occurring in the knee joint are associated with the abnormal accumulation of fluid in or around a joint, which can be bloody effusion or non-bloody effusion [36], [37], [38], [39], [40], [41]. As a kind of extracellular fluid, the effusion is more conductive than other tissues in the knee [42]. When effusion accumulates and distributes throughout the knee joint, its bioimpedance decreases due to the “short-circuit” effect. A few studies have shown that edema or effusion can lead to corresponding decrease in localized bioimpedance of various human body parts, as summarized in Table I. Moreover, the breaks or damages of cartilage or other tissues may also decrease bioimpedance since they provide more current flow...
Researchers have explored the relationship between bioimpedance and knee injuries. For example, Pichonnaz et al. measured the bioimpedance of legs after total knee arthroplasty surgery and then observed a clear relationship between bioimpedance and knee edema volume [44], [45]. Nevertheless, the electrode placement they adopted allowed them to measure the bioimpedance of the legs, not localize to the knees. Hersek et al. developed wearable devices to assess knee health based on bioimpedance measurement [46], [47]. The devices measured the bioimpedance of the knees using a tetrapolar electrode configuration with a sinusoidal injection current at 50 kHz, and the results showed 98.2% precision in detecting knee injuries. N. Turgunova et al. observed the changes at different frequencies from healthy and osteoarthritis knees using bioimpedance measurement with a bipolar electrode configuration, but the sample volume in the study was too small [48].

In this study, we validate the feasibility of the bioimpedance measurement with bipolar electrode configuration as a technique for detecting knee injuries without visible swelling. The Xiyan, an acupuncture point, was selected for the placement of the electrodes. Xiyan is an acupuncture point in traditional Chinese medical science, literally the “eye” of the knee. Xiyan are the two hollows formed when the knee is bent, immediately next to both medial and lateral to the patellar ligament and below the patella, as shown in Fig. 1(a) [51]. There is little ligament or skeleton closely beneath the Xiyan, ensuring that the

| Objective | Author & Year | Subject | Primary findings |
|-----------|---------------|---------|-----------------|
| Thoracic fluid | Pomerantz et al.(1989) [13], Zerahn et al.(1999) [15], Peacock et al.(2000) [17] | Patients with abnormal thoracic fluid or pleural effusion | The abnormal accumulation of fluids within the thorax reduced transthoracic bioimpedance, and the removal of these fluids increased the measured transthoracic bioimpedance. |
| Lymphoedema in Extremity | Ward et al.(1995) [18], Cornish et al.(1996) [19], Ward et al.(2009) [20], Scholler et al.(2012) [22] | Patients with lymphoedema in arms or foot | The affected extremity had lower bioimpedance compared to the unaffected extremity; the bioimpedance would gradually increase back to the healthy level during the recovery. |
| Burns | Kenworthy et al.(2018) [23], Edwick et al.(2020) [24] | Patients with minor limb burns (<5% total body surface area) | About 5% of healing odds would result in one ohm increase of the bioimpedance; the bioimpedance was highly correlated to the edema volume changes. |
| Tooth roots | Cosoli et al.(2017) [25] | Patients with inflammation or peri-implantitis | The localized bioimpedance was lower than healthy control when the patient had inflammation or peri-implantitis in tooth roots. |
| Brain | Gasser et al.(2002) [26] | Patients with brain tumors, intracranial hemorrhage, or hydrocephalus | The cerebral bioimpedances of the patients with brain tumors, intracranial hemorrhage, or hydrocephalus were lower than healthy controls. |
| Leg | Codognotto et al.(2008) [27] | Patients with arthropathy of lower limbs waiting for the surgeries | The bioimpedance became lower after the surgeries due to the edema, and the localized measurement had better sensitivity to such change. |

II. MATERIALS AND METHODS

A. Feasibility Study of Bipolar Electrode Configuration

1) Bipolar Electrode Configuration: In this study, two Xiyan of each knee were selected for the placement of the electrodes. Xiyan is an acupuncture point in traditional Chinese medical science, literally the “eye” of the knee. Xiyan are the two hollows formed when the knee is bent, immediately next to both medial and lateral to the patellar ligament and below the patella, as shown in Fig. 1(a) [51]. There is little ligament or skeleton closely beneath the Xiyan, ensuring that the
Three volunteers with healthy knees were recruited from the visitors and stayed still. None of them reported any discomfort or swelling due to injuries. The 45 healthy controls were recruited with electrode placement; 3. their knees had visible deformity or a lesion, anterior cruciate ligament (ACL) injury, and posterior cruciate ligament (PCL) injury [58], [59]. One noticeable common pathological feature in these injured knees is that they all had small to moderate amount of effusion. Patients would be excluded for the following situations: 1. they could not bend their knees; 2. their knees had unhealed skin traumas that interfere with electrode placement; 3. their knees had visible deformity or swelling due to injuries. The 45 healthy controls were recruited from other visitors to the hospital. Researchers confirmed that their knees were all healthy before being included in the control group.

2) Study Process Design: For each patient or healthy control, the knee bioimpedance measurement was conducted after their consent was obtained. The setup and process of bioimpedance measurements followed what was proposed in the feasibility study, except that the bioimpedance data of each knee were collected only once at 5 min DS. The reason for “5 min DS” is that the measured impedance values would be relatively stable when DS was more than 5 min, which will be illustrated in detail in the Results and Discussion sections. During the measurements, participants were required to lie on beds with their knees flexed to 90° and stayed still. None of them reported any discomfort or pain associated with the measurements.

3) Data Analysis Process: The Pearson Chi-square test was adopted to calculate the difference in sex ratio between the patient and control groups. The Kolmogorov-Smirnov test was used to calculate the differences in age, weight, height, and body
mass index (BMI). The patient group was not further divided into subgroups by different knee symptoms because our objective is to correlate the bioimpedance with knee injuries as a whole in this study.

Because body conditions vary significantly between different individuals, comparing both knees of the same person is more meaningful than comparing the knees of different individuals. Hence, the relative differences of bioimpedance between the healthy knee and the injured knee of the same person were calculated to explore the relationship between bioimpedance and injuries. The relative bioimpedance differences were calculated using the following formulas:

1) The patient group: \( \Delta Z_p = \frac{Z_i - Z_h}{Z_h} \)

2) The healthy control group: \( \Delta Z_h = \frac{Z_l - Z_r}{Z_r} \)

where \( \Delta Z_p \) and \( \Delta Z_h \) are the relative differences of bioimpedance between the two knees of patients and healthy controls, and \( Z_i, Z_h, Z_l, Z_r \) are the bioimpedances measured from injured, healthy, left, and right knee, respectively. The t-test was performed using IBM SPSS Statistics 25.0 software to compare the distributions of \( \Delta Z_p \) and \( \Delta Z_h \). The principal component analysis (PCA) and support vector machine (SVM) algorithms were used to classify these two groups, and the classification results are evaluated using the leave-one-out cross-validation (LOOCV).

4) Design of Portable Bioimpedance Measurement Device: Although SP-200 can measure the impedance accurately, it is relatively expensive (around $10,000 USD) and bulky, which is not suitable as a point-of-care device. After confirming that bioimpedance can be correlated to knee injuries, a prototype portable device was built. Our miniaturized design can measure impedance ranging from 100 \( \Omega \) to 100 \( kHz \) within 100 Hz to 1 MHz that meets the requirements of the spectrum needs for detecting knee injuries.

The circuit block diagram is shown in Fig. 3(a) while the actual print circuit board (PCB) design is shown in Fig. 3(b). The digital signals were generated and processed by Field Programmable Gate Array (FPGA). The direct digital frequency synthesis (DDS) was used to generate a sine wave at an arbitrary frequency in two’s complement format, which was then transformed into the analog converter (DAC) AD9742 (Analog Device, USA). The programmable gain amplifier (PGA) adjusted the magnitude of the excitation waveform to the proper level. The signal passed through a 6th Butterworth filter to filter out the quantized noise. The excitation waveform was applied simultaneously to the samples and the calibration resistor using 2-channel drivers. Afterwards, the signal went through TIA, PGA and were sampled using 2-channel analog-to-digital (ADC) LTC2323 (Analog Device, USA) at the sampling rate of 4.096 MSPS simultaneously. FPGA is used to store the two sampled signals and performed 4096 points Fast Fourier Transform (FFT) to obtain the magnitude and phase. The NOIS II, a processor inside FPGA, calculated the bioimpedance of the sample by
Fig. 3. (a) The circuit block diagram of the proposed portable bioimpedance measurement device, where Cyclone V is the FPGA development board P0192 (Terasic Technologies, Taiwan). (b) A photograph of the PCB design.

comparing their magnitudes and phases, which were sent to the computer via UART.

III. RESULTS

A. Feasibility Study of the Bipolar Electrode Configuration

With the bioimpedances measured from different DS, it was found that the declining trends of the measured bioimpedance magnitude were less significant after 5 min DS. Fig. 2(a) displays the reduction percentages of the measured bioimpedance magnitude in different DS segments. The reduction percentage is defined as a reduction in the bioimpedance magnitude measured at a specific DS segment. For example, the reduction percentage from 1 min DS to 5 min DS is expressed as

$$\text{Reduction Percentage}_{1 \sim 5\text{min}} = 100\% \times \frac{|Z_{1\text{min}}| - |Z_{5\text{min}}|}{|Z_{1\text{min}}|}$$

where $|Z_{1\text{min}}|$ and $|Z_{5\text{min}}|$ are the bioimpedance magnitudes measured at 1 min and 5 min DS, respectively. From 1 min DS to 5 min DS, the measured bioimpedance magnitude would reduce about 5% to 10% on average. By contrast, the reduction percentages in the rest of the DS segments were within 5%, especially for the frequency range from 46.4 kHz to 215 kHz, their reduction percentages being near zero with relatively small standard deviations. Thus, the results implicate that the measured bioimpedances were likely to be relatively stable when the DS reached 5 mins. In addition, the bioimpedances measured at 464 kHz and 1 MHz appeared probably irrelevant to different DS. The reduction percentages at 464 kHz and 1 MHz had notably large standard deviations ($\approx 20\%$) at all DS segments, while their averages were up and down around zero.

| TABLE II | Anthropometric Characteristics of the Patient Group and the Control Group |
|-----------------|-----------------|-----------------|
| | Patient Group (n=39) | Control Group (n=37) |
| Age (years) | 45.41(16.49) | 44.24(14.61) |
| Height (cm) | 167.01(9.24) | 168.81(8.83) |
| Weight (kg) | 65.18(12.07) | 68.67(13.78) |
| BMI (kg/m²) | 23.38(4.12) | 23.90(2.99) |
| Sex(male/female) | 20/19 | 24/13 |

*Asymptotic significances of age, height, weight, and BMI were calculated using the Kolmogorov-Smirnov test; The asymptotic significance of sex was calculated using the Pearson Chi-square test.*

Similar phenomena can also be observed in the bioimpedances of the knees measured at 5 min DS on four days. Fig. 2 shows a representative data set of the bioimpedance, which was measured from volunteer #2. The measured eight sets of bioimpedance data of the same individual varied vastly in the frequency range below 21.5 kHz. However, such kind of variation was much less in the mid-high frequency range. From 46.4 kHz to 215 kHz, most of the differences in the bioimpedance of two knees of the same individual measured on the same day were less than 15 $\Omega$. In addition, the bioimpedances in some data sets became irregular and tended to increase from 464 kHz to 1 MHz, which should only happen when the inductive reactance dominates the overall change of bioimpedance.

B. Bioimpedance Measurement of Knee Injuries

1) Anthropometric Characteristics of Study Subjects: The patient and control groups do not differ significantly in age, weight, height, body mass index (BMI), and sex ratio, as shown in Table II. Both groups cover the population with ages from 20 to 75 years old, and most of them are middle-aged. Additionally, the BMIs of both groups are mainly in the range of normal to slightly overweight, with no underweight or extremely obese individuals.

2) Relative Difference of Bioimpedance: The t-test results of $\Delta Z_p$ and $\Delta Z_h$ at different frequencies are summarized in Table III. Fig. 4(a) shows the distribution of $\Delta Z_p$ and $\Delta Z_h$ versus frequency using boxplots. Samples were rejected if there were any missing data or the measured bioimpedance of one knee was more than 2 times of the other one at $>400$ kHz or $<10$ kHz. This will be explained in the discussion section. The remaining valid samples used for the analysis consisted of 37 healthy controls and 39 patients. The most valuable results are the statistically significant differences between $\Delta Z_p$ and $\Delta Z_h$ at 46.4 kHz, 100 kHz, and 215 kHz, whose p-values are around 0.001. At these three frequencies, the average $\Delta Z_p$ is about 5%, whereas the average of $\Delta Z_h$ is nearly zero. Hence, 46.4 kHz, 100 kHz, and 215 kHz are used as the significant frequency sampling points (SFSPs) in the following discussion. On the contrary, there is no statistically significant difference between...
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### Table III

| Frequency | Patient Group $\Delta Z_p$ | Control Group $\Delta Z_h$ | t-test for Equality of Means  
(Equal variances not assumed) | Test for Equality of Variances |
|-----------|-----------------------------|----------------------------|-------------------------------|-------------------------------|
|           | n=39                        | n=37                       | Sig.                         | 95% CI                        |
| 1 MHz     | -5.66% (15.63%)             | 1.37% (13.23%)             | 0.0372                       | -7.04%                       | -13.65% - 0.43% 0.770      |
| 464 kHz   | -4.13% (12.57%)             | 2.17% (12.87%)             | 0.0342                       | -6.30%                       | -12.12% - 0.48% 0.594      |
| 215 kHz   | -5.55% (7.17%)              | -0.55% (6.49%)             | 0.0021                       | -5.00%                       | -8.12% - 1.87% 0.547       |
| 100 kHz   | -5.01% (6.36%)              | -0.22% (4.66%)             | 0.0004                       | -4.74%                       | -7.33% - 2.24% 0.114       |
| 46.4 kHz  | -4.36% (6.47%)              | 0.32% (4.64%)              | 0.0009                       | -6.07%                       | -7.34% - 2.00% 0.073       |
| 21.5 kHz  | -3.20% (8.30%)              | 0.92% (6.18%)              | 0.0161                       | -4.13%                       | -7.46% - 0.79% 0.295       |
| 10 kHz    | -1.92% (9.78%)              | 1.33% (7.58%)              | 0.1086                       | -3.25%                       | -7.24% 0.74% 0.406        |
| 4.64 kHz  | -1.42% (10.55%)             | 1.50% (8.36%)              | 0.1839                       | -2.92%                       | -7.27% 1.42% 0.500        |
| 2.15 kHz  | -1.06% (10.96%)             | 1.47% (8.91%)              | 0.2713                       | -2.53%                       | -7.09% 2.02% 0.517       |
| 1 kHz     | -0.97% (11.38%)             | 1.25% (9.59%)              | 0.3603                       | -2.22%                       | -7.02% 2.58% 0.562       |
| 464 Hz    | -0.82% (12.13%)             | 0.91% (10.69%)             | 0.5133                       | -1.72%                       | -6.94% 3.50% 0.586       |
| 215 Hz    | -0.69% (13.40%)             | 0.52% (12.64%)             | 0.6863                       | -1.21%                       | -7.16% 4.74% 0.728      |
| 100 Hz    | -0.55% (16.37%)             | 0.10% (16.29%)             | 0.8633                       | 0.65%                        | -8.11% 6.82% 0.940       |

3) Test of Proposed Portable Bioimpedance Measurement Device: The proposed portable bioimpedance measurement device was tested with some standard resistors to evaluate its precision and accuracy in terms of magnitude. The tests repeated 1000 times, and the precision and accuracy were evaluated using:

$$\delta_p = 100% \times \frac{\sigma_{1000}}{Z_{1000}}$$

$$\delta_a = 100% \times \frac{|Z_{1000} - Z_t|}{Z_t}$$

where $\delta_p$ and $\delta_a$ are the errors measured in precision and accuracy, $\sigma_{1000}$ and $Z_{1000}$ are the standard deviation and the mean of 1000 times measurement results. $Z_t$ is the measurement result of the SP-200. The test results at 100 kHz and the calculation results are shown in Table IV, which is the most significant frequency point in the bioimpedance results of the knee injury as shown in the Table III. The proposed bioimpedance measurement device presents high accuracy and precision from 200 $\Omega$ to 100 $k\Omega$, where $\delta_a$ is less than 0.5% and $\delta_p$ is less than 0.9%. The proposed device was also tested with 12 knees of 6 healthy volunteers. The results are compared with bioimpedance data...
and was mainly due to knee injuries. The average reductions in 10 kHz) and high (400 kHz) frequencies could be explained by closer and more stable contact between the electrode gel and the skin. Moreover, in our measurement results, the relationship between impedance magnitude and frequency as well as the evolution of impedance over DS are similar to that found by Hewson et al. [56]. At around 100 kHz, $C_{es}$ could be treated approximately as a short-circuit, which minimizes the total effect of electrode-skin impedance. Therefore, we could observe in the results that the bioimpedances measured at around 100 kHz varied much less on different days or at different DS. However, the inductance of leads and electrode-skin cannot be neglected when the frequency reaches the MHz level [42]. This probably can explain why the measured bioimpedance sometimes was higher at 1 MHz than at 464 kHz, and the bioimpedance measured at 464 kHz and 1 MHz was irregular to the increasing DS. Supplement to the two-resistor model proposed by Searle and Kirup [60], this model further explains the effects of skin-electrode in the high-frequency range. The simplified models in Fig. 6(b) briefly illustrate how the effective components of the external factors change with frequency. This model suggests that the variations caused by the external factors can be minimized at around 100 kHz with DS greater than 5 min.

In addition, the model also implicates the impedance measured at low (<10 kHz) and high (>400 kHz) frequencies could indicate whether the influences of external factors are similar between measurements, which provides an approach to find and reject invalid data. In the data analysis process, the relative differences of bioimpedance between both knees of the same person were calculated to explore the relationship between bioimpedance and injuries, which is also known as self-contrast. To further enhance the significance of self-contrast, it is necessary to ensure that the influences of external factors are similar in the bioimpedance measurements of the same individual’s two knees. Therefore, the samples were rejected if the measured bioimpedance of one knee is more than 2 times of the other one at low (<10 kHz) and high (>400 kHz) frequencies.

### B. Detection of Knee Injuries Based on the Bioimpedance

The self-contrast results of the patient group and the healthy control group are consistent with the theoretical prediction for the influence of knee injuries on the bioimpedance. The common knee injuries, including ligament tears, and menisci lesions, have effusion accumulation and damages of soft or hard tissues. The effusion, as a kind of high conductive component in the knee, have effusion accumulation and damages of soft or hard tissues. The effusion, as a kind of high conductive component in the knee, helps bridge a conductive path for the electrical current [47]. Moreover, tissue damage may also present less resistance to the electrical current, just like the dielectric difference between cortical bone and cancellous bone [43]. These changes in the tissue level inside the knee could be represented by the lower bioimpedance. In the data analysis results, the bioimpedance of the injured knee was usually around 5% lower than that of the healthy knee in the patient group at the significant frequency sampling points (SFSPs), where $\Delta Z_{h}$ was nearly zero. The knees of the same person are genetically identical and grow under the same environment, the healthy knee can be regarded as a healthy duplicate of the injured knee. Therefore, the about 5% bioimpedance reduction found in the $\Delta Z_{h}$ was mainly due to knee injuries. The average reductions in absolute value are 16.52 $\Omega$, 17.46 $\Omega$, and 18.88 $\Omega$ for 215 kHz, 100 kHz, and 46.4 kHz, respectively. Similarly, the average measured with the SP-200 at the same time. During the test, bioimpedance of the knee was first measured using the SP-200. Once the measurement was completed, the banana connectors (The electrode was connected to the lead, and the other end of the lead was a banana connector. Both the SP-200 and the proposed device have banana connectors.) were immediately switched to the proposed device and the bioimpedance of the same knee was measured by the proposed device. In this way, the proposed device and the SP-200 could measure the same objective without interference because they performed the bioimpedance measurement separately. Results obtained from the proposed device were compared with those obtained from the SP-200. The relative magnitude error and absolute phase error of the proposed device based on results from the SP-200 are shown in Fig. 5.

### IV. DISCUSSION

#### A. Implications From the Feasibility Study of Bipolar Electrode Configuration

The influence of primary external factors that affect the measured bioimpedance can be described by a simplified four-element equivalent circuit, as shown in Fig. 6(a). Increasing DS would lower $R_{es}$ and $C_{es}$ by allowing the electrode gel and the skin cuticle to touch more tightly, but this effect on the bioimpedance measured at high-frequency would be weakened drastically after 5 mins DS. The significant decrease of bioimpedance over time, which eventually levels off, can be explained by closer and more stable contact between the electrode gel and the skin.

#### TABLE IV

| Nominal value | $Z_{1000}$ | $\sigma_{1000}$ | $\delta_p$ | $\delta_{ps}$ |
|---------------|------------|----------------|------------|--------------|
| 237 $\Omega$ | 237.12     | 0.466          | 236.48     | 0.271%       | 0.197%       |
| 1.47 $\kappa\Omega$ | 1.466.24     | 2.646          | 1.467.25   | 0.069%       | 0.180%       |
| 4.22 $\kappa\Omega$ | 4.127.56     | 14.948         | 4.133.61   | 0.146%       | 0.362%       |
| 7.50 $\kappa\Omega$ | 7.311.51     | 31.728         | 7.342.92   | 0.423%       | 0.434%       |
| 10 $\kappa\Omega$ | 9.725.17     | 40.068         | 9.753.95   | 0.295%       | 0.412%       |
| 23.7 $\kappa\Omega$ | 233.059.97   | 145.458        | 233.354    | 0.206%       | 0.624%       |
| 47.5 $\kappa\Omega$ | 46643.91    | 349.363        | 46768      | 0.265%       | 0.749%       |
| 90.9 $\kappa\Omega$ | 87776.65    | 780.334        | 881.85     | 0.464%       | 0.889%       |
| 215 $\kappa\Omega$ | 205239.6    | 3017.96        | 211584     | 1.084%       | 1.442%       |

Fig. 5. Relative magnitude error and absolute phase error of the proposed device measured from 12 knees.
The absolute bioimpedance reduction found in Hersek’s study is 12.78 Ω, which was measured from 7 patients with unilateral knee injury using tetrapolar electrode configuration [47]. In addition, the results also comply with the implications obtained from the feasibility study. The bioimpedances measured at three SFSPs presented relatively small variances, corresponding to the frequency range which minimizes the influence of external factors in the proposed model.

The knee injury classifier achieved a sensitivity of 87.18%, but its specificity is only 72.97%. The distributions of the two groups’ PCs were distinguishable in the 2D plane, but the notable mix-up of the two clusters made it challenging to separate the two groups. The mix-up was attributed to the considerable variance resulting from external factors. The means of the $\Delta Z$ are almost equal to the standard deviations of $\Delta Z$ at the SFSPs. In other words, the average reduction degree of the bioimpedance due to knee injuries was similar to the measured bioimpedance error resulting from external factors. Therefore, the influence of external factors should be further minimized in the future to obtain better sensitivity and specificity.

However, considering that it is low-cost, portable, and easy-to-access, the bioimpedance measurement is still a promising technique to be implemented in the early diagnosis of knee injuries and the real-time monitoring of postoperative rehabilitation. The portable bioimpedance measurement device proposed in this paper meets the accuracy and frequency requirements for making the knee joint bioimpedance measurement. The measurement results are highly correlated to those of SP-200. Nevertheless, its cost is lower than USD $160 (the price can be further reduced if we map the design using system-on-chip). The device can sweep the frequency from 100 Hz to 1 MHz within 2 seconds. These features make it very suitable for point-of-care applications. In addition to the low-cost bioimpedance measurement system, many research groups also tried to develop reusable electrodes made of metal, carbonized rubber, or textile [61], [62], [63], [64]. These reusable electrodes do not use electrolytes or adhesive, so the skin irritation problems caused by sticking electrodes can be avoided [65]. With the help of inexpensive portable bioimpedance measurement systems and reusable non-stick electrodes, the bioimpedance measurement technique will become more affordable and convenient in the future. Moreover, by developing it into a wearable device, the bioimpedance data of the knee can be dynamically collected and then sent to the physicians for further consulting.

C. Limitations

In this study, we did not differentiate the severity or the types of knee injuries. The study also did not successfully construct the relationship between the phase change in bioimpedance and knee injuries. These remain objectives of future research. Moreover, the influence of external factors should be further minimized in future research to obtain better sensitivity and specificity.

V. Conclusion

This study validated the feasibility of the bipolar electrode configuration for knee bioimpedance measurements and investigated the relationship between bioimpedance and knee injuries. The feasibility study revealed that the measurement error induced by external factors could be minimized at around 100 kHz with > 5 min DS. Furthermore, the bioimpedances measured at other frequencies can indicate whether the influences of external factors are similar between measurements. The self-contrast results indicated that knee injuries could reduce bioimpedance by an average of 5%. Using the principal component analysis (PCA) and support vector machine (SVM) for the sample binary classification based on the knee bioimpedances at the significant frequency sampling points (SFSPs), the classifier achieved a sensitivity of 87.18%. In addition, we proposed a low-cost, portable bioimpedance measurement device that satisfies the accuracy and frequency range needs for the knee joint bioimpedance measurements. In conclusion, our results indicate that the portable and inexpensive bioimpedance measurement technique is promising for detecting and monitoring knee injuries.

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[47] S. Hersek et al., “Wearable vector electrical bioimpedance system to assess knee joint health,” IEEE Trans. Biomed. Eng., vol. 64, no. 10, pp. 2353–2360, Oct. 2017.

[48] N. Turgunova, V. Velikaya, L. Musabaeva, A. Aleinik, I. Anisenya, and N. Martemyanov, “Bioimpedance spectroscopy for clinical assessment of tissues and the irradiated cancer tumors,” in Proc. 7th Int. Forum Strategic Technol., 2012, pp. 1–4.

[49] S. Wold, K. Esbensen, and P. Geladi, “Principal component analysis,” Chemometrics Intell. Lab. Syst., vol. 2, no. 1–3, pp. 37–52, 1987.

[50] C.-C. Chang and C.-J. Lin, “LIBSVM: A library for support vector machines,” ACM Trans. Intell. Syst. Technol., vol. 2, pp. 1–27, 2011.

[51] P. Deadman, M. Al-Khafaji, and K. Baker, A Manual of Acupuncture. East Sussex, U.K.: J. Chin. Med. Pub., 1998.

[52] S. Benn, A. Datir, and A. Saifuddin, “Synovial recesses of the knee: Mr imaging review of anatomical and pathological features,” Skeletal Radiol., vol. 38, no. 4, pp. 317–328, 2009.

[53] S. Grimes and D. G. Martinson, “Sources of error in tetrapolar impedancemeasurements on biomaterials and other ionic conductors,” J. Phys. D Appl. Phys., vol. 40, no. 1, pp. 9–14, 2006.

[54] Y. M. Chi, T.-P. Jang, and G. Cauwenberghs, “Dry-contact and noncontact biopotential electrodes: Methodological review,” IEEE Rev. Biomed. Eng., vol. 3, pp. 106–119, 2010.

[55] D. J. Hewson, J.-Y. Hogrel, Y. Langeron, and J. Duchêne, “Evolution in impedance at the electrode-skin interface of two types of surface emg electrodes during long-term recordings,” J. Electromyogr. Kinesiol., vol. 13, no. 3, pp. 273–279, 2003.

[56] C. Sidebottom, H. Rudolph, M. Schmidt, and L. Eisner, “IEC 60601–1—the third edition,” J. Med. Device Regulation, p. 9, May 2006.

[57] K. G. Shea et al., “Management of anterior cruciate ligament injuries,” JBJS, vol. 95, no. 20, pp. 1885–1886, 2013.

[58] M. A. Markow, D. W. Nance, and R. F. Subel, “Biomechanics of human joint surfaces,” J. Biomech., vol. 34, no. 9, 2013, Art. no. R47.

[59] R. Kusche, S. Kaufmann, and M. Rychlik, “Dry electrodes for bioimpedance measurements—design, characterization and comparision,” Biomed. Phys. Eng. Exp., vol. 3, no. 1, 2018, Art. no. 015001.

[60] S. L. Colyer and P. M. McGuigan, “Textile electrodes embedded into underwear fabric for electrocar-dio-grammetry (ECG) monitoring,” Materials, vol. 11, no. 2, 2018, Art. no. 256.

[61] Y.-Z. Baek, J.-H. An, J.-M. Choi, K.-S. Park, and S.-H. Lee, “Flexible polymeric dry electrodes for the long-term monitoring of ECG,” Sensors Actuators A Phys., vol. 143, no. 2, pp. 423–429, 2008.

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