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# Novel Method of Using Dynamic Electrical Impedance Signals for Noninvasive Diagnosis of Knee Osteoarthritis

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*Abstract*—**Osteoarthritis (OA) of knee is the most commonly occurring non-fatal irreversible disease, mainly in the elderly population and particularly in female. Various invasive and non-invasive methods are reported for the diagnosis of this articular cartilage pathology. Well known techniques such as X-ray, computed tomography, magnetic resonance imaging, arthroscopy and arthrography are having their disadvantages, and diagnosis of OA in early stages with simple effective noninvasive method is still a biomedical engineering problem. Analyzing knee joint noninvasive signals around knee might give simple solution for diagnosis of knee OA. We used electrical impedance data from knees to compare normal and osteoarthritic subjects during the most common dynamic conditions of the knee, i.e. walking and knee swing. It was found that there is substantial difference in the properties of the walking cycle (WC) and knee swing cycle (KS) signals. In experiments on 90 pathological (combined for KS and WC signals) and 72 normal signals (combined), suitable features were drawn. Then signals were used to classify as normal or pathological. Artificial multilayer feed forward neural network was trained using back propagation algorithm for the classification. On a training data set of 54 signals for KS signals, the classification efficiency for a test set of 54 was 70.37% and 85.19% with and without normalization respectively *wrt* base impedance. Similarly, the training set of 27 WC signals and test set of 27 signals resulted in 77.78% and 66.67% classification efficiency. The results indicate that dynamic electrical impedance signals have potential to be used as a novel method for noninvasive diagnosis of knee OA.**

## I. Introduction

OSTEOARTHRITIS (OA) is one of the most common irreversible joint disease in the body. It is estimated that about one fifth of population will be affected by arthritis in the U.S. by the year 2020 [1]. More than 15% of adult population in the UK has long-term health problems due to arthritis and related conditions [2]. Significant proportion of population above the age of 45 years is affected by this non-fatal, but crippling disease. Its prevalence is more in women than men. OA and its other related conditions increase dependency of elderly on others, and result in enormous losses in medication, and later surgery, thereby affecting Nation's economy [3], [4]. Although hip OA is more common in the western population, Indians and South East Asians have more incidence of knee OA [5], [6]. OA is widely considered to be a chronic disease with joint degeneration via wear and tear, along with other symptomatic and asymptomatic changes in and around knee. The main risk factors involved in the etiology of osteoarthritis are: ageing, mechanical stress or abuse, hereditary and/or constitutional factors, and inflammation [7]. In the manifested stage of the disease, in general, all the structures of the joints are affected, viz. bones, articular cartilage, synovial membrane, joint capsule, and associated musculature. It is a very slow process and the most common associate symptoms such as pain, reduction in the amplitude of movement and thick synovial membrane are developed much after the disease has been progressed [8].

Taking X-ray images of the diseased knee is the most commonly method used for the diagnosis of OA since Kellgren and Lawrence proposed grades of knee OA. Unfortunately, it is not effective in the early period of etiologic changes since X-rays show joint space narrowing and other developments of OA when it is in irreversible stages. Other methods such as arthroscopy, arthrography, ultrasound, magnetic resonance imaging, etc., fail to deliver a cost effective, simple to use, and suitable solution for mass screenings and repeated use. The diagnosis of osteoarthritis is still a challenge in the biomedical engineering and different ways are being explored [9]-[12].

Bioelectric impedance can be considered for a powerful tool in diagnosis, and/or medical research. Main advantages of using bioelectric impedance are its noninvasive nature, low cost and ease of operation. There are many applications of using bioimpedance signals for different pathological conditions, but its use in diagnosis of knee OA needed to be explored in detail. Electrical conductivity and its distribution change with development and progress of OA as suggested by various theoretical considerations [13]-[15]. When healthy control group and pathologic OA group were used to study the effect of loading on the knee electrical impedance, the fluctuations during different loading states and the area under load duration curve were markedly different in the normal and OA study group [16]. In one other study done in static conditions, bioelectrical impedance measurements using bioimpedance spectroscopy were made to compare intracellular and extracellular resistance [17]. We have reported our experiments for comparing dynamic impedance

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changes in knee swing cycle and walking cycle experiments elsewhere [18], [19], but the classification aspects needed to be studied. Our present study is an attempt to use the electrical impedance signals using knee swing and walking cycle data – which reveals the dynamic impedance changes – to train and test classification for noninvasive diagnosis of the knee OA.

## II. Methodology

### A. Subject Selection

Persons with normal knee are called as control group (CG) and with pathological knees are termed as OA group (OAG) in this paper. The selection was done after consultation with medical practitioners. Guidelines from American Rheumatology Association were followed for inclusion and exclusion criteria [20]. Age, sex, height, weight, history of knee, pain, relevant medical history, etc. were recorded. Two self-assessment questionnaires were filled in showing the pain, stiffness and functional difficulty (disability) level, viz. Lequesne Index [21], and Western Ontario and McMaster University's Osteoarthritis Index (WOMAC) Index [22]. Ethical clearance was taken for the project. The subjects were explained about the experiment and consent on a specially prepared format was taken. In the analysis, we have considered each knee as one subject even though they may have come from the same person. The characteristics of the subjects are given in Table I.

### B. Data Acquisition

Electrical impedance signals (EIP or IPG) around knee of subjects were recorded for the offline analysis. Tetra-polar impedance plethysmography was used to record impedance changes. Two outer electrodes insert very low amplitude and high frequency constant current around the knee, and voltage is measured using inner two electrodes. The measured voltage thus can give estimate of knee segment as impedance (Z). The schematic for the study is shown in Fig. 1.

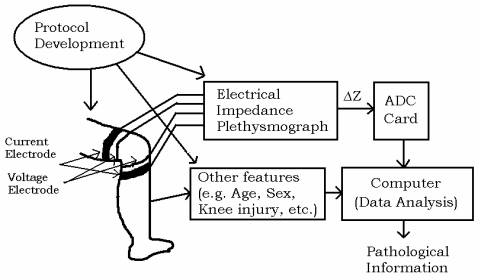


Fig. 1. Schematic of experiments

All subjects were asked to relax for 10 minutes before each recording. The subjects were explained about the experiment protocol. Specially prepared ring type braided-wire silver-coated electrodes were placed above and below knee-cap (patella) with approximately 15 cm distance between the measuring electrodes (see Table I). Current electrodes were of double the width than measuring ones for better penetration of current. Standard electrolytic gel was used on the electrodes.

In Knee Swing experiments, each subject sat on a rigid table with his/her legs suspended over the edge. Then the subjects were asked to repeatedly extend his/her leg from 90° to 0° (where 0° is when leg is straight and parallel to the floor, and 90° is when leg is suspended towards floor) in about 2 s, then flex from 0° to 90° in the same time. A full knee swing cycle (KS) is defined as the extension and flexing combined. Base impedance (or static impedance) was recorded when knee was at relaxed condition at 90°. For Walking Cycle (WC) data, subject walked to-and-fro on a pathway of around 30 feet inside the laboratory. Base impedance was recorded in standing posture while balancing body weight on both the feet equally in relaxed state. A marker signal was also recorded for events like 0°, 90°, heel-touch and toe-off. Base impedances were later used to see the effect of amplitude normalization.

The ΔZ output from plethysmograph (Bionics Ltd., India) was used to record bidirectional changes in impedance. It was digitized by ICPDAS® PCI digitizer card interfaced to a standard PC using LABVIEW® interface. The digitized data was stored in ASCII files for offline analysis. Sampling frequency was chosen as 1000 Hz, which was later down-sampled to 256 Hz by MATLAB® programming in offline analysis.

### C. Signal Processing

Raw signals were pruned to select the KS cycles and WC cycles. Six KS cycles from each knee data were chosen by observation of zero crossing. Three walking cycles with similar temporal characteristics were chosen. As mentioned in Table I, total of 8 control knees and 10 OA knees were used for the analysis. This amounted to 48 control signals (1 cycle as one signal) and 60 OA signals for the KS, and to 24 control signals and 30 OA signals for WC analysis. The signals were used without amplitude normalization in one case and were normalized *wrt* base impedance of 33 ohms using base impedance value of static impedance in another case. Low pass filtering with cutoff frequency of 40 Hz was done to remove all the high frequency noise. All KS signals were time-normalized to 4 seconds and WC signals were normalized to 2 seconds.

### D. Feature Selection

Variance and RMS values of all the signals were used as temporal features for all the subjects. Energy in band (band power) of 0-5 Hz was used as frequency domain feature. These features were selected because two-tailed t-tests showed statistical significance between the means for the CG and OAG (see Table II).

### E. Artificial Neural Network Training and Classification

A multiple-layer feed forward neural network (ANN) having 6 nodes in input layer, 12 neurons in hidden layer, and 1 neuron in output layer was used for training and

classification. The output layer had log-sigmoid transfer function and the other two layers had tan-sigmoid transfer function. For training, backpropagation method was selected with Levenberg-Marquardt algorithm. This ANN was used because it can train multilayer networks with differentiable transfer functions to perform function approximation, pattern association, and pattern classification. The training and test sets comprised of 50% each from the available signals. The classification efficiency, false positives and false negatives were calculated after simulating the ANN with the test set. Efficacy of normalization *wrt* base impedance was also checked by repeating the procedure.

## III. Results

We found that the static (base) impedances were quite overlapping for the CG and the OA group. The mean of means of the impedance signals of the two groups showed that the difference in the means is not significant (Table II). After the two-tailed *t*-tests, differences in means of variances, RMSs and energy in 0-5 Hz band were found to highly significant ($p<0.00001$). When the WC signals without normalization were used for training, the trained NN gave 66.67% classification efficiency. After normalization, it was 77.78%. In both cases, the false positive percentage remained same as 25%. The false negatives in WC without normalization case were more. For KS signals, the classification efficiency was found to be 85.19% and 70.37% without and after normalization respectively. The false positives were below 25% and false negatives were below 40 % in both cases. The classification results are summarized in Table III.

## IV. Discussion

Looking towards the limitations of the presently available means to diagnose knee OA non-invasively, there is a need to develop a simple, cost-effective solution. Although research efforts are on for innovative ideas, none so far has reached to the clinical level. Use of electrical impedance data for diagnosis of knee OA has been proposed for early diagnosis of OA, but the technique has not been extensively studied so far. Earlier communications were suggestive about use of EIP for diagnosis of knee OA [16]-[19]. Automated (computerized) diagnosis and classification could be done if EIP signals could be used with suitable features for training and classification methods.

As shown in Table III, there is substantial difference in the temporal and frequency-domain properties of the control group and OA group. Hence when just three features (variance, RMS, and band-power in 0–5 Hz) were used for training ANN, the network converged fast. The test set resulted in reasonably good efficiency (70–85%). The false positive percentage was very less ($\leq$25%) which was good for a small test set. Although the false negative percentage was slightly on the higher side, it also showed values less than 25% in 2 out of 4 cases of testing. The experiments show that the EIP data can be used as a novel method for the noninvasive diagnosis of knee OA.


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## TABLES

Table I. *Subject Characteristics*

| *Variable* | *Number of subjects (knees)* | *Number of Knee Swing Cycles* | *Number of Walking Cycles* | *Age, years (mean±SD [a])* | *BMI [b], kg/m$^2$ (mean±SD)* | *Distance between measuring electrodes, cm (mean±SD)* | *Base Impedance, Ohm (mean±SD)* |
|---|---|---|---|---|---|---|---|
| Control Group | 8 | 48 | 24 | 53.4±8.5 | 26.9±2.9 | 15±0.707 | 28.9±4.034 |
| OA Group | 10 | 60 | 30 | 62.4±3.5 | 24.8±1.6 | 15.2±0.752 | 30.1±4.594 |

[a] *SD=Standard deviation,* [b] *BMI=Body mass index (weight in kg/(height in m)$^2$)*

Table II. *Comparison of parameters*

| *Parameter* [a] | | *Control Group* | | *OA Group* | | *t-tests for difference in means for significance* | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *KS* [b] | *WC* [c] | *KS* | *WC* | *p-value assuming equal variances* | | *p-value assuming unequal variances* | |
| | | | | | | *KS* | *WC* | *KS* | *WC* |
| Band Power (0-5 Hz) [d] | WN [e] | 5017±1830 | 879±330 | 3235±1885 | 433±190 | $2.89\times10^{-6}$ | $8.64\times10^{-8}$ | $2.82\times10^{-6}$ | $1.15\times10^{-6}$ |
| | AN [f] | 7588±1987 | 1126±322 | 4331±2079 | 528±250 | $4.73\times10^{-13}$ | $4.09\times10^{-10}$ | $4.60\times10^{-13}$ | $2.90\times10^{-9}$ |
| Mean | WN | 0.00±0.03 | -0.03±0.04 | 0.00±0.03 | -0.01±0.03 | 0.812* | 0.058* | 0.812* | 0.066* |
| | AN | 0.00±0.03 | -0.03±0.04 | 0.00±0.03 | -0.01±0.03 | 0.812* | 0.058* | 0.812* | 0.066* |
| Variance | WN | 9.79±3.57 | 3.41±1.29 | 6.31±3.68 | 1.69±0.74 | $2.91\times10^{-6}$ | $1.04\times10^{-7}$ | $2.84\times10^{-6}$ | $1.35\times10^{-6}$ |
| | AN | 14.8±3.88 | 4.37±1.25 | 8.45±4.06 | 2.07±0.97 | $4.82\times10^{-13}$ | $5.30\times10^{-10}$ | $4.72\times10^{-13}$ | $3.79\times10^{-9}$ |
| RMS | WN | 3.08±0.55 | 1.82±0.37 | 2.41±0.72 | 1.26±0.32 | $5.47\times10^{-7}$ | $2.42\times10^{-7}$ | $2.83\times10^{-7}$ | $5.04\times10^{-7}$ |
| | AN | 3.82±0.50 | 2.08±0.32 | 2.83±0.69 | 1.40±0.36 | $2.66\times10^{-13}$ | $1.49\times10^{-10}$ | $5.97\times10^{-14}$ | $1.10\times10^{-9}$ |

[a] *Values given as x±y are mean±SD,* [b] *KS=Knee Swing Cycle signals,* [c] *WC=Walking Cycle signals,* [d] *Band power is in arbitrary units,* [e] *WN=Without Normalization wrt base impedance,* [f] *AN=After Normalization wrt base impedance,* * *Not significant.*

Table III. *Comparison of classification efficiencies*

| *Signal set* | *Classification count* | | *n/N*[#] | *Percentage* |
|---|---|---|---|---|
| Walking Cycle signals | No. of correct classifications | WN [a] | 18/27 | 66.67% |
| | | AN [b] | 21/27 | 77.78% |
| | No. of false positives [c] | WN | 3/12 | 25.00% |
| | | AN | 3/12 | 25.00% |
| | No. of false negatives [d] | WN | 6/15 | 40.00% |
| | | AN | 3/15 | 20.00% |
| Knee Swing Cycle signals | No. of correct classifications | WN | 46/54 | 85.19% |
| | | AN | 38/54 | 70.37% |
| | No. of false positives | WN | 1/24 | 4.17% |
| | | AN | 5/24 | 20.83% |
| | No. of false negatives | WN | 7/30 | 23.33% |
| | | AN | 11/30 | 36.67% |

[#] *n/N is number count by total count,* [a,b] *As in Table II,* [c] *False positive is normal person identified as having OA,* [d] *False negative is OA person identified as normal*