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Evaluating the Effect of Capacitance Model on Tibia Fractured Limb Healing Diagnosis.

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ABSTRACT

Fracture healing prediction using electric simulation has gained attraction by orthopedic surgeons in recent years. The present study aims at development of mathematical correlation of capacitance model on parameters such as Resistance (conductance) and duration for tibia fractured limb patients treated under DC electric stimulation. Model parameters performances were evaluated using linear regression method. The dependence of model on Resistance(conductance) and duration is demonstrated using simple mathematical correlation. Moreover, the effect of model on diagnosing of fracture healing is explained using the electrical data recorded across 32 different tibia fracture patients whose fracture site was stabilized using Teflon coated rings and a DC input voltage of 0.7V was applied via K-wires. All groups of tibia fracture patients under dc electric stimulation exhibit a regular pattern of conductance and capacitance was inferred in this study. The steep fall in conductance and capacitance after an initial irregularity reaching the lowest level indicated the healing of fracture is the novelty of the work. The 32 patients were classified into 4 group's namely fresh presentation, presentation after a medium delay, presentation after a long delay and facture with gap. The data was subjected to linear regression analysis and R^2 validation which exhibited minimum Standard Error (SE).

Keywords: Fracture union, SE, capacitance, linear regression

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INTRODUCTION

Increase in Road accidents has resulted in the most common injury namely the bone fractures treated by orthopedic surgeons. Fracture treatment involves lengthy period of lost man-days, with soaring expenditure involved in health care. The need is to exactly predict the time of healing i.e. when the bone has regained adequate strength to be loaded in the normal manner. However during the course of treatment of any fracture, it is complex to predict at which time exactly a given fracture has united. This knowledge of the exact time at which a fracture unites is vital for both the patient and the medical practitioner in order to reduce the immobilization time and refracture risk. Moreover, there is every chance of accidental mistakes so that a fracture may be loaded prematurely or unloaded long after the actual union. X-rays are used to determine fracture healing which has many demerits [1-4].Fracture healing assessment comparing stiffness measurement was done using radiographs [5].Biomechanics involved in bone healing was discussed briefly [6].

The lack of consensus in the assessment of Fracture healing among orthopedic surgeonsand need of novel technique for fracture healing prediction involving Concepts of fracture union, on-union and delayed union was emphasized [7-8].Selection, evaluation and indications for electrical stimulation of ununited fractures was explained in brief [9].Interlocked Intramedullary nailing for open fractures of tibia shaft was discussed[10-11]. Recently electrical stimulation was tried as a method to diagnose fracture healing [12-14]. Still the closing assertion in the papers is that these fractures are in the process of healing. There is no exact prediction of fracture healing. In an attempt to simplify the fracture healing process, models have been proposed to relate all possible data and observation to understand this process better. Some authors have proposed a first order system, which has been tested and validated only on animals [15-18]. In order to have more insight about the fracture healing process mathematical models have been proposed as an alternative method to monitor fracture healing using electrical data recorded across human tibia fracture and its healing diagnosis usingmodel parameter process gain has been proposed. Current stabilization in terms of process gain parameter becoming constant indicates the healing of fracture [19].Fracture-healing predicted by empirical models and neural network were compared and error analysis performed [20].

The above authors have not analyzed the effect of capacitance model on fracture healing prediction statisticallyusing electrical data recorded across limb for humans. In this work the dependence of capacitance on Resistance (conductance) and duration is demonstrated using simple mathematical correlation. Moreover, the effect of capacitance on diagnosing of fracture healing is explained using the electrical data recorded across 32 different tibia fracture patients. Current stabilization in terms of Resistance (conductance) becoming constant indicates the healing of fracture.The model parameters outcome was validated using linear regression technique. This method was implemented to test fracture healing prediction for thirty two patients at Thanjavur Medical College.

The article is structured as follows: Section 2 discusses about methodology for modeling tibia fracture, Section 3 development of mathematical correlation for capacitance model for tibia fracture. Section 4 discusses about validation of mathematical model through statistical method. Section 5 deals with Results and Discussion while Section 6 concludes this work.

METHODOLOGY

Modeling overview

When an intact bone is broken there will be two pieces, for example A and B as shown in Figure 1. The gap between the two pieces will not be empty but filled with blood clot. If the electric current is passed from one end of the unbroken bone by an electrode, it reaches the electrode at the other end by the conduction property of an intact bone. If one attempts to test the same conduction through a fractured bone as in Figure 1, the current from the electrode passes through the fragment A, then the blood clot and then the fragment B, before reaching the other electrode. The fracture site blood clot is considered as a dissimilar material between the two fractured fragments of bone A and B.

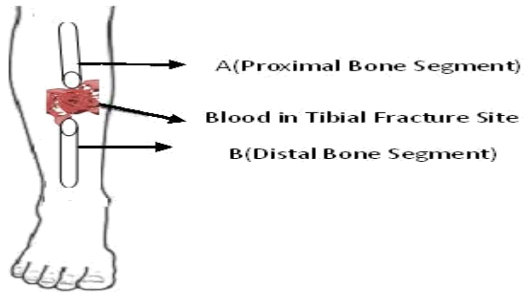


Figure 1: Broken bone

When a current is applied this is considered as a di-electric and electrical conduction of a blood clot supported by the studies [20-21] is also realized in our previous study by mathematical and empirical methods. Hence we consider the tibia fracture site as a capacitance. Once the fracture site hematoma heals to become bone and becomes continuous with the two fragments A and B, the original conductivity and resistivity of an intact bone is restored to near normal.

Participants involved

In this study 32 tibia fracture patients subjected to fracture healing by diagnostic DC simulation were studied. As a regular pattern of current i.e. initial irregularity in the current flow and its stabilization in later stage were observed in all the cases, Modeling for four different fracture cases is demonstrated.The 32 patients were classified into 4 groups namely fresh presentation (patient was presented to practitioner within 2 weeks) , presentation after a medium delay (patient was presented to practitioner within a period more than 2 week but within 2 months) and presentation after a long delay (presented to practitioner after 2 months) and Fourth group were facture with gap. For all the four different groups (case) of patients same fracture healing pattern was obtained.

Materials involved

A carbon Ilizaro external fixator ring fixator is fixed across the tibia fracture site on a patient. Carbon ring fixators are stronger, lighter and radiolucent. 5mm diameter threaded rods were used to connect the carbon rings and 1.8mm(316L stainless steel) K-wires were used to fix the bone to the carbon rings by wire-fixation bolts [13].Carbon -rings were chosen in this study of electric conduction as there are no conducting material across and the current is recorded across the fracture. Carbon Ilizaro external fixator were mobilized with partial to full weight bearing in the immediate postoperative period as allowed by the patient's pain tolerance. The upper wire of the fracture was given a DC voltage up to 1 V and the output was recorded across the fracture in the lower wire.

Statistical Analysis

The 32 patients were classified into 4 groups. During DC electric stimulation treatment for every patient in the Follow-up period, the resistance and conductance was calibrated.Using linear regression analysis R^2value, residual and standard error was calculated.

EXPERIMENTAL SETUP

The experimental set-up for fracture healing model analysis is shown in Figure 2. Data from the prospective study that was conducted where open fractures of tibia were treated was used in this study [15-16].The open fractures were cleaned of debris and contaminants and were stabilized with four Teflon coated carbon ring -Ilizarov external fixators. In these cases the healing was followed with clinical assessment and periodical X-rays till the endpoint of fracture union and then the rings were removed. Additionally, all the patients also had application of electrical voltage in the range of 0.1-1.0 V DC in 0.1 V increments, across the two wires on either side of fracture. The output current was recorded by an ammeter connected in series. Ammeter measures the current flow across the fracture .Using the ammeter reading as reference the online data recording of voltage calibration in terms of current is done. The Schematic representation alone is shown in the experimental set up. The wired diagram is published by one of the authors in references [13-16].The Ammeter output was connected to M/s AD Instrumentation 16 channel data acquisition card via signal conditioning unit. The card was connected to the USB port of the Pentium processor with an in-built anti aliasing filter. The card supports 16 ADC and

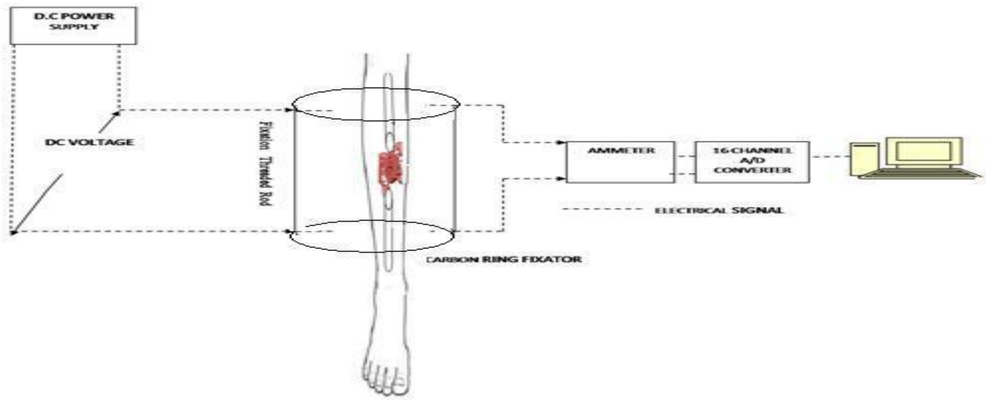


Figure 2: Experimental set-up for fracture healing model analysis

DAC channels in the range of ±15V .Program was developed in 'C' language to read and display the patient's current rating in terms of mA. The graph was compared with the appearance of new bone formation in X –rays. The above methodology was carried upon twelve different patients at Thanjavur Government Medical College to predict the exact instance at which a fracture has united completely. For all the twelve different patients same fracture healing pattern was obtained. The real time experimental data for four tibia fracture patients is shown in figure 3.In figure3 Case-1 shows the output response recorded during fracture treatment using DC electric simulation for one of the fresh presentation patient to the clinician. Case2 corresponds to response of a medium delay patient while Case3 corresponds to long delay more than 2 months. Case 4 shows the response of a patient presented with a fracture gap and was presented after 2 months delay to clinician.

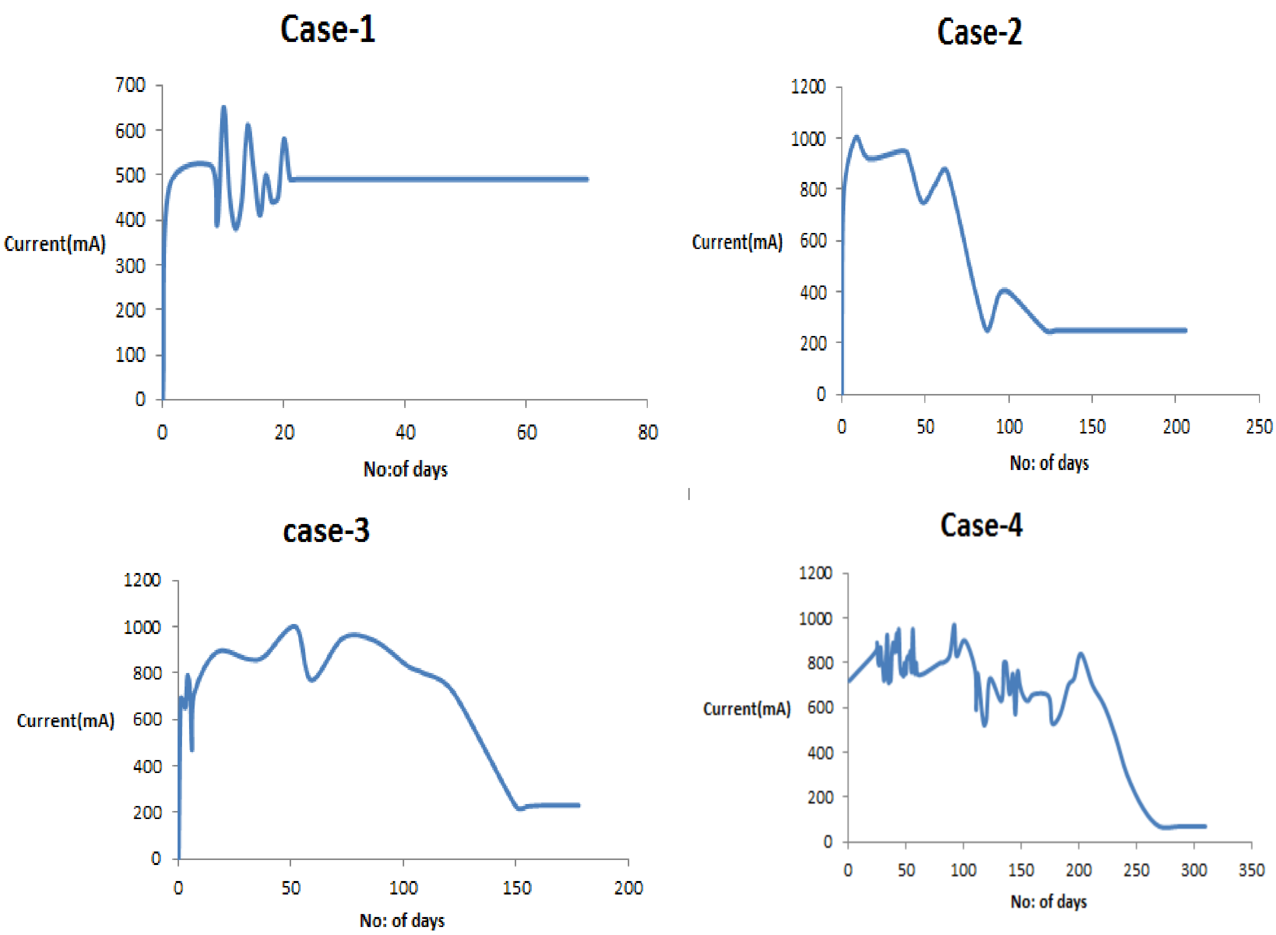


Figure 3: Experimental data collected from open loop response of a four tibia fracture patient cases

MATHEMATICAL CORRELATION FOR CAPACITANCE MODEL

The tibia fracture was analyzed, in modeling point of view as two broken parts of bone with blood in between acting as capacitor [19]. We know Capacitance

$$C = \frac{Q}{V} \tag{3.1}$$

Where 'Q' is the charge in Coulomb and 'V' is the Voltage in Volts. The Charge is defined as product of Current' I' in Ampere and time period 'T' in seconds. Here in our tibia fracture model 'T'is follow- up period in days as fracture healing process is complex and healing happens in various stages consuming days to repair the tissue, regenerate and remodel.

$$Q = I * T \tag{3.2}$$

By ohms law

$$V = I * R \tag{3.3}$$

where I is the current in Ampere , R is the Resistance in Ohm .Substitute 3.2 and 3.3 in 3.1 Capacitance becomes

$$C = \frac{T}{R} \tag{3.4}$$

$$C \propto \frac{1}{R} \tag{3.5}$$

$Let \frac{1}{R} = G$ where 'G ' is the conductance in mho hence capacitance C becomes

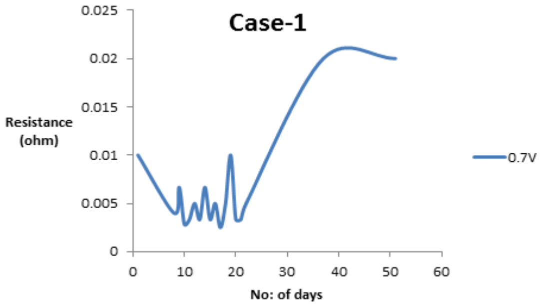
$C = GT$ (3.6)

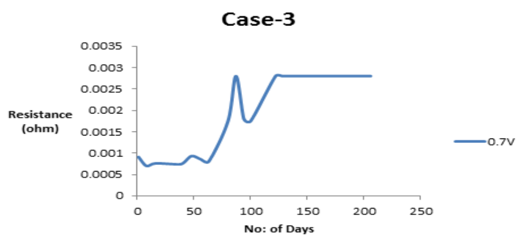
Hence from equation 3.5 and 3.6 it is substantiated that capacitance depends on Resistance (conductance) and follow up-period.

MODEL VALIDATION

Resistance and Conductance Calibration

For a Dc applied voltage of 0.7V the Resistance was calibrated using equation (3.3) for four different groups of patients. Figure 4 shows the change in resistance for the patient follow-up period. Figure 5 shows the change in conductance G calibrated for the patient follow-up period.





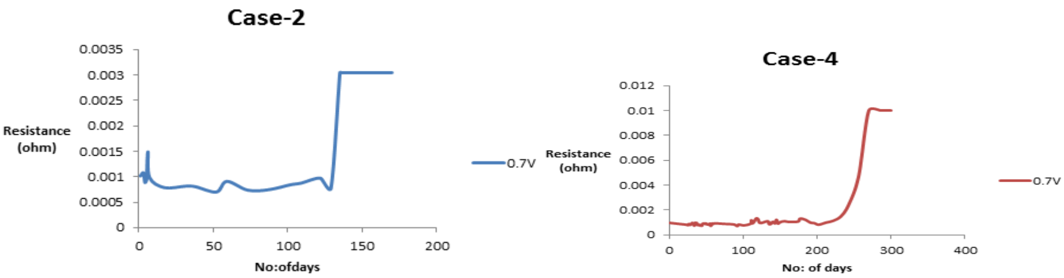


Figure 4: Variation of Resistance fromopen loop response of a four tibia fracture patient cases

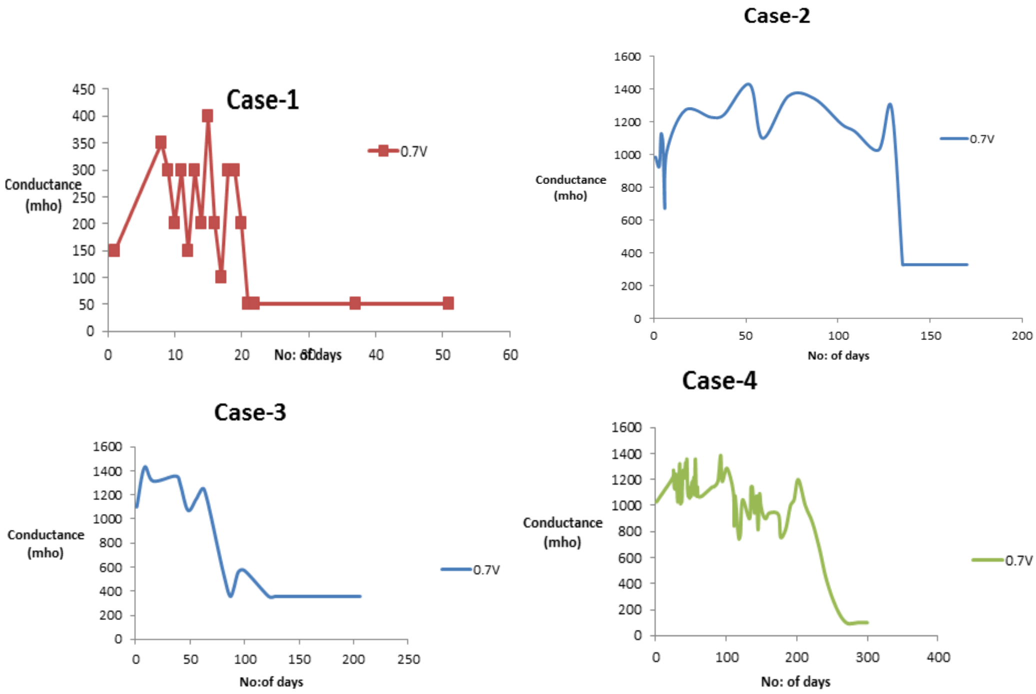
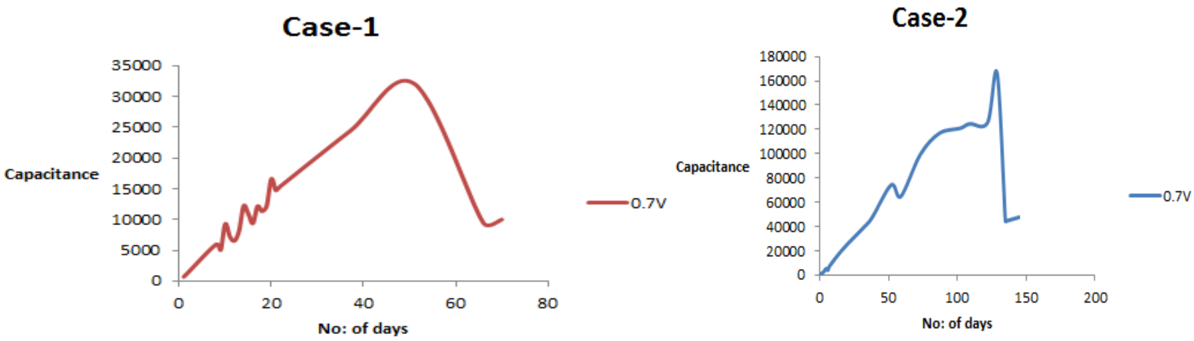


Figure5: Variation of Conductance fromopen loop response of a four tibia fracture patient cases



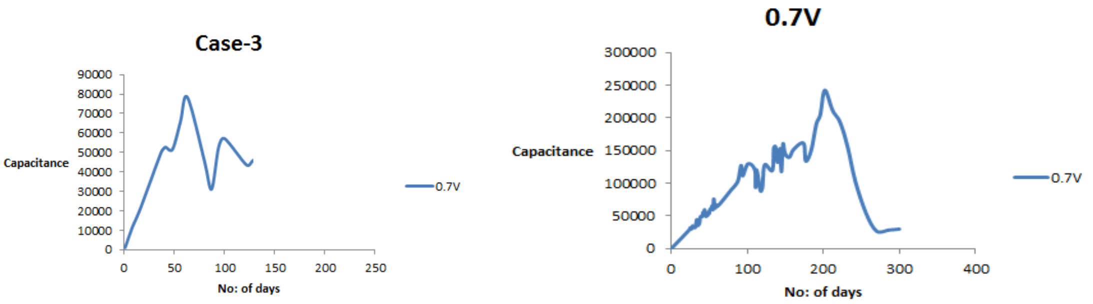


Figure6: Variation of Capacitance fromopen loop response of a four tibia fracture patient cases

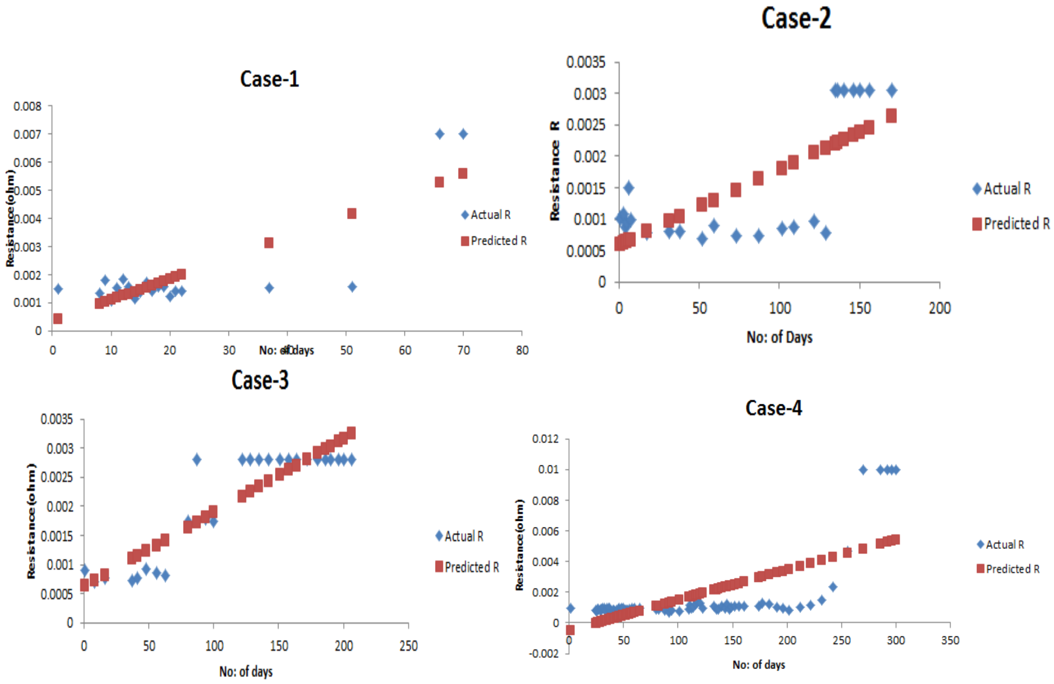


Figure 7: Linear Regression Analysis for Variation of Resistance

Linear Regression Analysis

Linear regression analysis for various resistances calibrated for different tibia fracture patientsisshown in figure7. Residuals calculated for Predicted Resistance for Case-1 tibia fracture patients is shown in table1.From table1 we observe that error between the actual and predicted model output is minimum.It was observed from table 2 that R^2 value varied from 0.5 to 0.8 and with the minimum standard error

Table 1: Residuals calculated for Predicted Resistance for Case-1 tibia fracture patients.

Observation	Predicted R	Residuals	Standard Residuals
1	0.000420935	0.001068427	1.106414959
2	0.000945022	0.000401132	0.415394151
3	0.001019892	0.00077498	0.802534731
4	0.001094761	-1.78381E-05	-0.018472348
5	0.001169631	0.000352108	0.364627604
6	0.0012445	0.000597605	0.618852802
7	0.00131937	0.000271539	0.281193718
8	0.00139424	-0.000246699	-0.255469999
9	0.001469109	-9.65602E-05	-0.099993368

10	0.001543979	0.000163338	0.169145812
11	0.001618848	-0.000218848	-0.226629558
12	0.001693718	-0.000102809	-0.106464265
13	0.001768588	-0.000213032	-0.220606397
14	0.001843457	-0.000636561	-0.659193616
15	0.001918327	-0.000489755	-0.507168655
16	0.001993196	-0.000564625	-0.584700252
17	0.00311624	-0.001594501	-1.65119391
18	0.004164415	-0.002573506	-2.665006956
19	0.005287459	0.001712541	1.773430968
20	0.005586937	0.001413063	1.463304581

Table 2: Regression statistics calculated for Predicted Resistance for tibia fracture patients.

Patient Group	Regression Statistics	Value
Group-1	Multiple R	0.727063
	R Square	0.528621
	Adjusted R Square	0.49916
	Standard Error	0.003774
Group-2	Multiple R	0.71048
	R Square	0.504782
	Adjusted R Square	0.482272
	Standard Error	0.000724
Group-3	Multiple R	0.902363
	R Square	0.814259
	Adjusted R Square	0.80652
	Standard Error	0.000403
Group-4	Multiple R	0.687889
	R Square	0.473191
	Adjusted R Square	0.466437
	Standard Error	0.001635

RESULTS AND DISCUSSION

In case 1 Tibia fracture the fracture was presented immediately without any delay. The initial irregularity in conductance and capacitance was measured till 15 days and later started to be constant from 18th day onwards. The steep fall in conductance and capacitance reached the lowest level on the 18th day and correlated with clinical and radiological sign of healing. This being our first case only in this case we waited for at least ten weeks so that good consolidation occurred. The rings were removed on the 70th day. Similarly case2 and case3 tibia fractures were presented in medium and prolonged delay in time and was treated with DC current electric simulation stabilization was obtained on 126th and 139th days respectively.

In the fourth case, Tibia fracture patient had bone loss and hence no contact presented, moreover this patient had internal bone transport. The maximum conductance and capacitancetook 60 days due to infection, the high-energy injury and frequent surgeries. The steep fall in conductance and capacitancereached the lowest level on the 220th day and correlated with clinical and radiological union. This may be the cause of irregularity with few peaks in the initial days of recording. The rings were removed on the 230th day.

Table 3: Comparison of Fracture Healing Prediction.

S.No	Case	X-Ray Healing indication in days	Experimental Output (Healing indication) in days
1.	Case1	18	18
2.	Case2	135	135
3.	Case3	139	139
4.	Case4	220	220

In all these cases the current, resistance, conductance and capacitance as observed from figures 3,4,5 and 6 was initially irregular varying nonlinearly, decreased and stabilized indicating that healing process is completed that was confirmed using x-rays. The stabilization of electric current flow matched with the period when the patient was able to weight bear comfortably. The Comparison of Fracture healing prediction methods with x-ray are shown in table3.From table 3 it is inferred that fracture healing predicted using pattern of capacitance and conductance matches with x-ray diagnosis.

At present we have diagnosed fracture healing across a single fracture site. It would be interesting to know the application of mathematical correlation across a multiple fracture site to understand the limitation of the mathematical correlation of the capacitance model developed.

CONCLUSION

Development of mathematical correlation of capacitance model on parameters such as Resistance (conductance) and duration for tibia fractured limb patients treated under DC electric stimulation was done. The various groups of tibia fracture patients under dc electric stimulation exhibit a regular pattern of conductance and capacitance was inferred in this study. The steep fall in conductance and capacitance after an initial irregularity reaching the lowest level indicated the healing of fracture.

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