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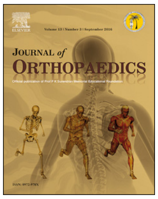

Electromagnetic simulation for diagnosing damage to femoral neck vasculature: A feasibility study☆

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ABSTRACT

Background: Femoral neck fractures are common injuries managed by orthopedic surgeons across the world. From pediatrics to geriatrics, disruption of the blood supply to the femoral neck is a well-recognized source of morbidity and mortality, oftentimes resulting in avascular necrosis of the femoral head. This devastating complication occurs in 10–45% of femoral neck fractures. Therefore, it is vital for orthopedic surgeons provide efficient treatment of this injury, in order to optimize the patient's potential outcome and prevent long-term sequelae.
Methods: In this study, the anatomy of the proximal femur, including femoral metaphysis, femoral neck, vasculature, and femoral head, were simulated in COMSOL Finite Element Analysis (FEA) software. Electric fields were generated in a fashion that exploited disruptions within the vasculature of the femoral neck. This study was aimed at developing an alternative imaging modality for narrowing or disrupting the femoral neck's vasculature. The variables used for investigation included: frequency, penetration depth, and magnitude of the electrical energy. These variables, when combined, allowed for enhanced simulated visualization of the vasculature of the femoral neck and theoretically expedited diagnosis of obvious, or occult, femoral neck injury.
Results: Simulated blood vessels were developed in two-dimensions: the phi direction (circular), and z-direction. Two different frequencies, 3 GHz, and 5 GHz were considered, with 100-J energy pulses within blood vessels of 2.54 mm in diameter. The fat surrounding the bone to the outside surface body was simulated at 0.25 inch (0.65 cm). An additional model, with layered fat and skin above the vessels, was simulated at 2000J and successfully able to visualize the femoral neck's blood vessels. Results showed a distinguished E field across the blood boundary of nearly 170 V/M.
Conclusions: The electric field simulation data within the Phi and Z directions promises the feasibility of a subsequent practical model.

1. Introduction

Femoral neck fractures are a challenge routinely faced by orthopedic surgeons. With an aging population, there is an increasing incidence of low-energy femoral neck fractures from a ground level fall. Furthermore, some femoral neck fractures are often the result of high-energy trauma in younger patients, as a result of shear forces across the patient's femoral neck. These injuries are particularly complex given their notoriously fragile blood supply.

The blood supply to the femoral head is the result of three main arterial sources and their branches: the medial femoral circumflex artery, lateral femoral circumflex artery, and terminal branches of the obturator artery.[8] Fractures, most commonly in elderly with osteoporotic bone and comorbidities, results in direct disruption of this blood flow. The result of this disruption of blood flow is avascular necrosis (AVN) of the femoral head and neck if anatomic reduction is not immediately restored through surgical intervention.[4] Various classifications by Garden[2] and Pauwels[3] have been developed in order to aid clinicians in the swift diagnosis and ideal management of this challenging patient population. Nonetheless, Current literature have identified that nearly 7% of all femur fractures have an ipsilateral femoral neck fracture.[7] These injuries are frequently missed amongst trauma patients and advancing protocols have been developed to aid clinicians in this diagnosis.[5]

The increased concern around this injury aims at preventing the known sequelae of avascular necrosis of the femoral head. While current literature has found an increased rate of AVN with the severity of displacement, non-displaced or occult fractures can also lead to osteonecrosis. The elevated risk of avascular necrosis and the high rates of non-union[1,6] make the management of this injury a challenge for all

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☆ The contribution of Dr. Rizkalla was related to the sensors and electromagnetics area. Dr. Salma contributed to the comparison of medical imaging approaches. Dr. James Rizkalla introduced the medical issue from his clinical expertise with Baylor University. Matthew Jeffers completed the investigation and received the COMSOL data at the ECE Department at IUPUI.

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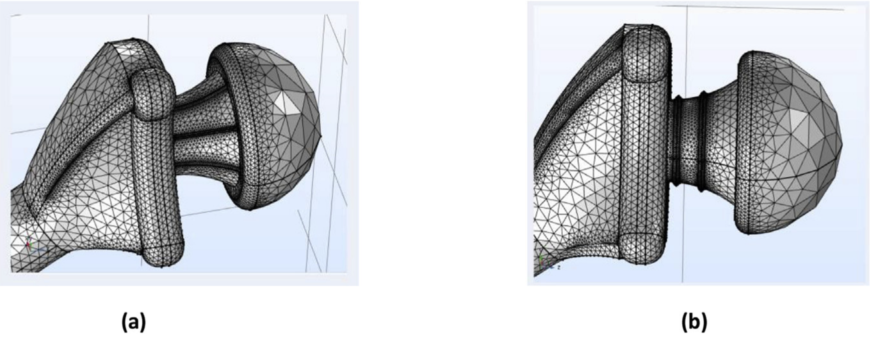

Fig. 1. The z and phi Blood Vessels Used for the Simulation: (a) for the z-direction, and (b) for the phi direction.

Table 1
Material properties used in the simulation.

Material	Frequency	Relative permittivity	Conductivity (mho/m)
Bone	2 Ghz	4.9	0.15
	5 Ghz	0.8	0.21
Muscle	2 Ghz	55.4	1.45
	5 Ghz	49.6	2.56
Fat	2 Ghz	15	0.35
	5 Ghz	12	0.82

Table 2
Vessel sizes used in the simulation.

Dimension	Normal	Small	Big	Closed
Z	0.075	0.035	0.1	0.01
Phi	0.05	0.025	0.1	0.01

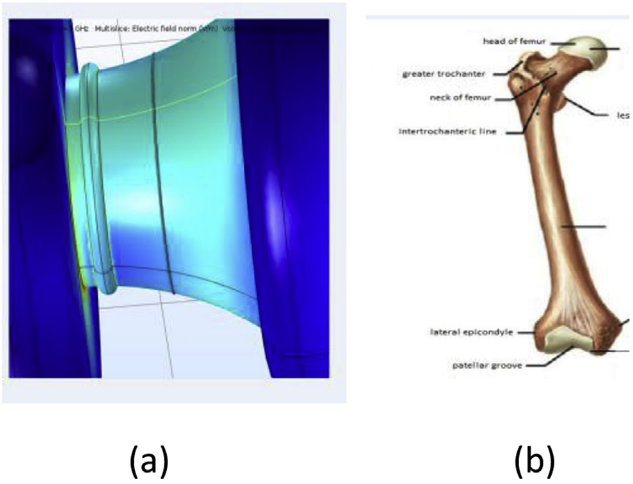

Fig. 2. The Femur with compoents and blood vessels: (a) the COMSOL Model, (b) the Femur components.

parties involved in the patient's care.

Currently, trauma patients are triaged and imaged, most commonly, using preliminary X-rays to visualize a patient's injuries. Radiographic images are often all that is needed to confirm the diagnosis of a femoral neck fracture—though advanced imaging is oftentimes utilized for inconclusive cases. CT scanner and MRI are useful tools for challenging diagnostic cases. However, CT scans subject patients to elevated levels of radiation while MRIs are unfavorable from a time and cost standpoint—being one of the more expensive imaging options for patients. Alternative imaging methods are challenging the current “gold standard” for evaluation of femoral neck fractures, in hopes of finding an efficient, reliable, and fiscally responsible modality. In this study, an alternative approach is proposed using electrical fields. With an electric field scan, transmission properties of simulated arteries, bone, and surrounding fat/skin can be used to evaluate an alternative imaging option. This paper details the control parameters of such an investigation.

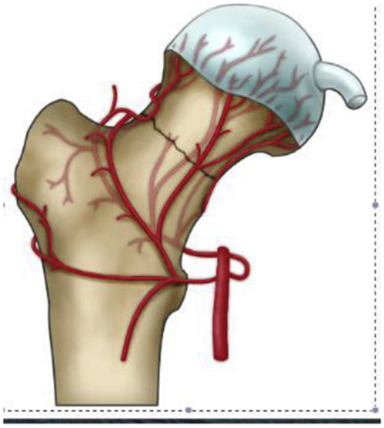

Fig. 3. Blood Vessels showing rapture in the femur.

2. The EM models

The wave equation used in the determination of the E distribution is given below:

$$\nabla \text{ x } (\nabla \text{x} E) = \nabla\ (\nabla . E) - \nabla^2 E$$

From Gauss ‘law, $\nabla.\ D = \rho_v$, then $\nabla.\ E = \rho_v/\varepsilon$.
Using $\rho_v = 0$, the wave equation becomes:

$$\nabla \text{ x } (\nabla \text{x } E) = - \nabla^2 E$$

The electric field is given in the form:

$$E = E_0\, e^{-\gamma z}$$

where γ = Propagation constant determined from:

$$\gamma^2 = - \omega^2 \mu \hat{\varepsilon}$$

Where $\hat{\varepsilon}$ is the complex permittivity given as:

$$\hat{\varepsilon} = \varepsilon(1\text{-}j\sigma/\omega\varepsilon)$$

Where $\varepsilon = \varepsilon_0 \varepsilon_r$, the radian frequency, $\omega = 2\pi f$, and σ is the conductivity.

The propagation constant, γ, is given by:

$\gamma = \alpha + j\beta$, where α is the attenuation constant, and β is the phase shift constant. The electric field is then given by:

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