Perception based Biomechanical Model Reduction for Needle Insertion Training Simulators

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Abstract

In modern clinical practices where minimally invasive procedures have become important medical techniques, the needle insertion is one of the vital elements [1]. In most of the medical residency's, the training techniques for needle insertion procedures by the novice is the apprenticeship method which can have a risk at the patient's safety [2]. Medical simulators have several benefits over traditional training such as training the physicians with both common and rare cases by changing the tissue properties [6]. The current state-of-the-art needle insertion simulations are reviewed in detail [5]. The literature models have not included the biomechanical and psychophysical concepts in the force feedback experienced by a trainee. The main objective of this paper is to develop analytical models of needle insertion including the biomechanical and psychophysical concepts that precisely captures the needle-tissue interaction forces. The experiments are performed based on the constraints required for the needle-tissue interaction force measurement would include the influence of three parameters [7]: method of needle insertion, needle characteristics, tissue characteristics

The needle-tissue interaction forces during needle insertion into soft tissues are classified into three forces: Tissue compression force, F_c, Tissue puncture force, F_p, Frictional force, F_f. The dynamics of needle interaction with tissue is studied, and several bio-mechanics based models are developed to estimate needle-tissue interaction forces using these experimental data.

Tissue compression force, F_c: To predict the force-deformation response of needle-tissue interaction during the compression phase, a four-parameter Burger's model [4] is being employed. The model has the following response equation

$$F + p_1 * \dot{F} + p_2 * \ddot{F} = q_1 * \dot{x} + q_2 * \ddot{x} \tag{1}$$

where

$$p_1 = \lambda_1[1 + \frac{E_1}{E_2}] + \lambda_2; \qquad p_2 = \lambda_1 * \lambda_2$$
$$q_1 = \lambda_1 * E_1; \qquad q_2 = \lambda_2 * \eta_1$$
$$\lambda_1 = \frac{\eta_1}{E_1}; \qquad \lambda_2 = \frac{\eta_2}{E_2}$$

where F is the contact force, E_1 and E_2 are tissue stiffness, η_1 and η_2 are tissue damping coefficient, x is the needle tip displacement, and dot denotes differentiation with respect to time t.

Tissue puncture force, F_p: The tissue puncturing phase further is divided into two events:

Crack initiation: The axial force applied by the needle tip during the crack initiation (F_{ci}) is estimated by

$$F_{ci} = 2 * \sigma_Y * A_t * sin\left(\frac{\alpha}{2}\right) \tag{2}$$

where A_t is the contact area between the needle tip, α is the angle between edges of the needle tip and the tissue and σ_Y stress in the tissue surface.

Needle propagation: The dynamic force for needle propagation (F_{np}) is expressed as [3]

$$F_{np} = \frac{4 * F_c * tan(\alpha/2)}{3 * w_c} \tag{3}$$

where w_c is the crack thickness equal to the needle outer diameter.

The total needle puncture force is expressed as

$$F_p = F_{ci} + F_{np} \tag{4}$$

Frictional force, F_f: It is modeled as an extension of seven parameter model [5] as:
when sticking,

$$F_f(x) = \sigma_0 x \tag{5}$$

when sliding,

$$F_f(v,t) = \left(F_c + F_s(\gamma, t_d) \frac{1}{\left(\frac{1+v(t-\tau_e)}{v_s} \right)^2} \right) sgn(v) + F_v v + \pi * (d_2 - d_1) * x * \sigma$$

where

$$F_s(\gamma, t_d) = F_{S,a} + \left(F_{s,\infty} - F_{S,a} \frac{t_d}{(t_d + \gamma)} \right)$$

where σ_0 tangential stiffness of the static contact, F_c is the Coulomb friction, F_s is the Stribeck friction, τ_e is the temporal parameter of the rising static friction, v_s is the characteristic velocity of Stribeck friction, $F_{S,a}$ and $F_{S,\infty}$ is the Stribeck friction at the end of the previous sliding period and after a long time at rest respectively, t_d is dwell time, which is the time spent at a certain stage of the process, σ is the empirical constant, d_2 and d_1 are outer and inner diameter of the needle respectively. In this model, the Stribeck friction parameter is considered with velocity, v after a certain time, γ.
The force feedback which is perceived during the insertion must be measured and included in the model as the trainee has the control of these forces. A block diagram of the needle-tissue interaction model is shown in Fig. 1. Incorporating human perception filter over the biomechanical models for needle-tissue interaction enhances the model by reducing the computational complexity without changing the perception of forces experienced by the trainee.

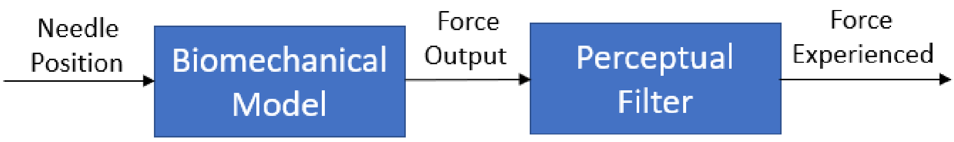

Figure 1: Block diagram of Needle-tissue interaction model with the perceptual filter

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