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RELIABLE AUTOMATED NEEDLE INSERTION SYSTEM FOR MEDICAL APPLICATION

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Abstract

Many disorders occur annually as a result of poorly performed stings. This project is an attempt to develop a system that automates blood tests, serum injections and catheter placements, and to identify its basic limitations. Determining parameters are first identified. They include the coordinates of stinging point on the skin, the depth of blood vessel, its radius and the age of patient. The developed module performs the sting process based on the knowledge of these parameters. Automation is based on a neural network which correlates the data to determine insertion angle and needle geometry. Though the insertion process is adapted to patient profile, difficulties still remain concerning correct skin viscoelastic properties as proper input parameters. However, finer analysis of skin-needle system indicates the possibility of a secure and much easier automated sting in a large range of usual parameters with constant speed.

Keywords

Robotic-Assisted Needle Insertion, Artificial Neural Network, Skin and Living Tissues Models

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1. Introduction

During recent period robotic systems have been given remarkable technical properties mainly due to impressive technological advances in Material Sciences and in more sophisticated Control Theory and Software advances. Enormous progress has been accomplished in actuation, sensor and computing fields which cover main aspects of the problem to give a machine the ability to perform a prescribed task. Such a challenge is however far from being solved. If very precise action can be ordered a robot, this is requiring favorable conditions for guaranteeing its completion. More explicitly if asymptotic stability criteria are mathematically known, they only operate if restrictive conditions are satisfied. One of them is a “good” enough environment description, and intuitively it is understandable that very stiff environments are easier to handle than “soft” ones, because power fluxes can be more easily controlled as they need less degrees of freedom to represent them. Soft systems are absorbing power coming from the acting system in a way which is not completely mastered and inevitably leads to power dumping in wrong places with often erroneous displacements. One possibility to counteract this defect is to give the system a robustness property which typically should guarantee that for any adverse and unexpected event taking place within the global system including the environment, the target will be reached. In general again conditions have to be satisfied and robustness is only obtained inside a ball in representative state space which may be too restrictive if power flux is itself bounded by system constraints. Despite a large body of research aiming at giving a solution to the control of interaction between a stiff object and a soft environment (Okamura et .al., 1999) (or the reverse), the problem is still open because the physics of the interaction is difficult to represent accurately enough, in order to remove the very contradictory requirement of monitoring a too precise output in a too soft environment. Defining where the "reasonable" border is located is not yet solved and in many cases specific solutions are researched in a trial and error way. A neat example of such a situation is Health action. Living tissues are often very soft ones and intervening tools are in general very stiff ones. Medical operators need very long practice time to get the feeling of living organism reaction, being also understood that this reaction is often specific to each patient. In present study, the elementary problem of automatically stinging a syringe across the skin of a patient to reach a blood vessel inside his/her body has been addressed. This problem gathers all the adverse ingredients mentioned above, and it represents an interesting example for evaluating the potential of "modern" methods applied to actual patient parameter range. It will appear that if some elements can be determined in accurate enough way, such is not the case for living body ones for which interpolative neural network methods will be tested. The results indicate that, owing to the incurred risk, system mastery requires more advanced data base to handle the relatively large range of human parameters an automatic stinging machine will face in normal application.

2. Experimental Protocol and Methods

The aim of the project is to find the parameters required to perform reliable needle control during injection in superficial under-skin blood vessels. Here veins will be mainly considered as they are usually more reachable. To get a reliable database on the elements of such system, a survey based on the testimony of nurses has been first documented. According to them, the relevant parameters are vein diameter and depth, patient age, and the amount of blood to be drawn. Patient age is important because old persons are more likely to have rolling veins (rolling veins are often due to medication) which imposes a larger attack angle for more efficient penetration. Vein depth is also an important parameter since the deeper the vein is, the larger the attack angle should be. Another important factor is the amount of blood to remove. The number of tubes to be filled is necessary to choose correct needle diameter though, independent of blood quantity to be drawn, nurses will choose needle size adapted to patient veins. In addition to these common parameters, one should take into account the stiffness of the skin, which is automatically included from intensive practice in nurse action when penetrating the needle in the skin. Here the skin will be approximated by a linear viscoelastic tissue characterized by two parameters, Young modulus and Poisson ratio. In order to see their effects, finite elements method has been used to model skin deformation under needle insertion. After discretization, the deformation is first evaluated at each node from static equilibrium equation. This leads to a set of 2n linear equations:

$$u = K * f \qquad (1)$$

where n is the number of nodes, u the displacement vector, f the force vector, and K the stiffness matrix which depends on Young modulus and Poisson ratio (Bro-Nielsen ,1997).

To simulate soft body distortions, a theoretical contact model has been developed to represent the forces implied in needle insertion. This model enables to size the needle (bevel angle, needle diameter) once patient profile is defined. The contact mechanics problem can be solved with Hankel transforms (DiMaio and Salcudean, 2005). The following steps can be defined

1) At first only the needle tip undergoes the skin resistance. The stiffness force Fst(z)is given by the following expression:

$$Fst(z) = 2\square E_r \tan(\square) z^2 \qquad (2)$$

where z is the penetration depth, □ the bevel angle and E_r the reduced modulus defined as

$E_r^{\square 1}$ = [E_1] + [E_2] with E_1, E_2 the needle and the living tissue Young moduli and [E_j] = □ □$_j$E /(1□□ $_j^2$), j=1,2, and □$_j$ the needle and the living tissue Poisson ratios

2) Then, as the needle penetrates the tissue, the force is composed of the friction forces and the cutting force Ffr-cut(z)

$$F_{fr\text{-}cut} \quad 2 \quad [E_2]D^4/E_1 I\}^{1/12} z + C \qquad (3)$$

with □ the friction coefficient, D the needle diameter, I the needle moment of inertia and C the cutting force

3) At needle withdrawal the only force left is frictional one

$$F_{fr}(z) = .325 \square \square D[E_2]\{\square^{\square} \ [E_2]D^4/E_1 I\}^{1/12} \quad (4)$$

Such a system description is missing two more degrees of freedom corresponding to alignment of syringe with the vein for needle insertion. To include this additional displacement for better design and architecture, parts have been designed with Blender, and realized with a 3D printer. To enable the system to learn the best action depending on the patient, a multi-layer perceptron useful to classify data (Abolhassani et. .al. 2007) has been trained with input vectors composed of the parameters influencing insertion, and with output class determining needle motion. First important step is feature evaluation, which enables to rank the features in decreasing order of importance, and is determined from learning process for each one of them so that they can be compared. Second one is the selection of features number to be used.

This step is iterative. First the learning with best feature is started, next with first two features, and so on. The i-th best feature is added attach new iteration. Last step was to modify network complexity: number of hidden layers, number of neurons per layer and learning rate. With a limited pool of examples to learn, a high learning rate has been preferred to speed up the learning process.

3. Results

3.1 Modeling and Machining Needle Insertion Module

The stepper motors (blue pieces) enable translations along x-axis, needle rotation (red piece) around x-axis and needle insertion/withdrawal. Module displacements are possible thanks to the main support (yellow piece) enabling translation along z-axis, and the additional support (green piece) moved by a motor along x-axis. With present improved design, space is preserved in the central part of main support. Now, the needle can be moved along x-axis.

3.2 Neural Network

Practically, adaptation of NN structure to database size is an important guideline for network structure design .Figure 3 shows the success rate depending on the number of used features. The red line depicts the test performed on test database, and the blue one the test on learning database. The higher success rate is obtained with 4 features, see Figure 3.

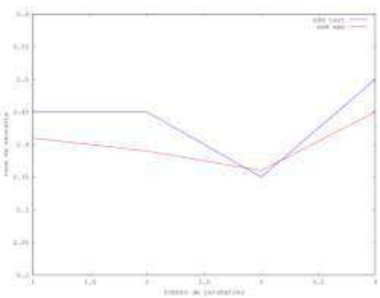

Figure 3: *Success Rate for Each Feature and for Different Number of Features*

One can compare the output class obtained with the network (“Classe”), to the targeted output class (“Classe Reelle”), see Figure 4. Only 50% predictions are correct, and output class 1 is never obtained as a consequence of too small number of samples.

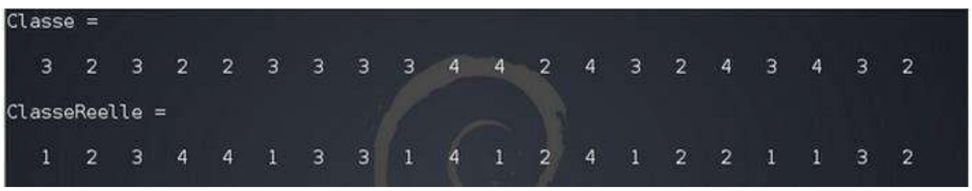

Figure 4: *Results of Neuronal Process*

Success rate has been tested for different network configurations. Best rate (70%) is obtained with 3 layers of 4 neurons, see Figure 5.

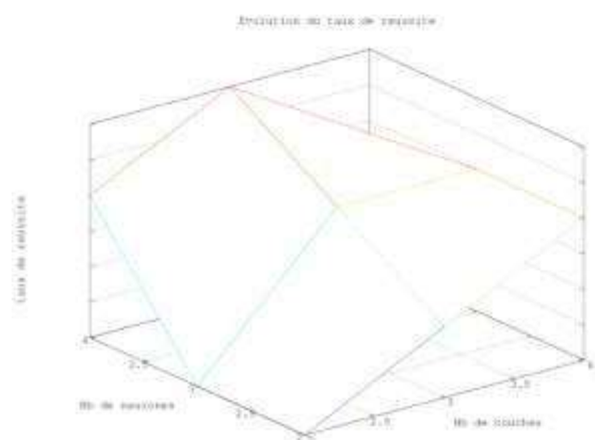

Figure 5: *Variation of Neural Network Success Rate*

The value of success rate can be explained by the scarcity of examples in learning database. Generally speaking, the network needs to learn during long time an important set of data. Here, when fed with a new input pattern, the network is unable to interpolate the data and to find the right output class.

3.3 Modeling Interaction between Needle and Living Tissues

Taking Young modulus and Poisson ratio of a patient [7], [10], needle insertion has been simulated. Two important parameters are needle diameter and bevel angle

A-Needle diameter: Force required for insertion with same bevel angle but with a different diameter is shown on Figure 6.

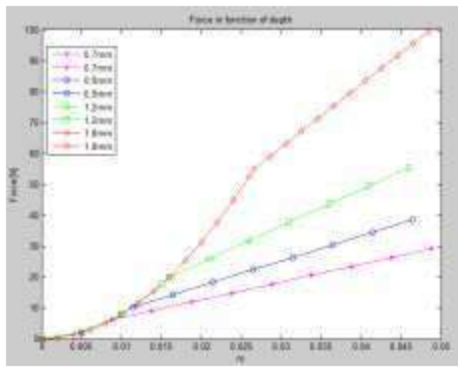

Figure 6: *Applied Force to the Needle vs Needle Diameter*

The first part of the curve is modeled by a second degree polynomial. During this phase the needle tip deforms the skin without penetrating into it. In this simulation it can be seen that curves are superimposed until skin rupture. From this moment on, the needle goes through the skin. During this phase, the measured insertion force is a compound of friction and cutting forces. The total force is modeled by a straight line.

B- Bevel Angle: In this simulation, needle diameter is fixed, and bevel angle is varied to evaluate its influence on the force acting on the skin. Bevel angle intervenes only during first phase. It is seen that the smaller is the angle, the faster the skin ruptures, see Figure 7.

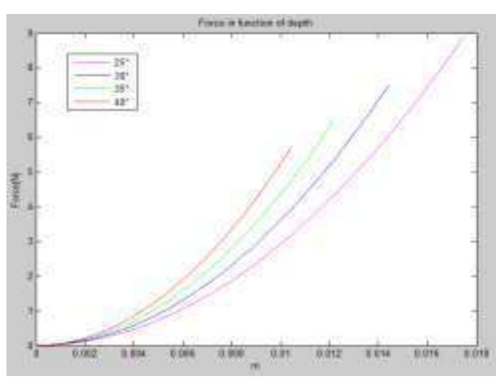

Figure 7: *Needle Applied Force vsNeedle Bevel Angle*

4. Adaptation of Bevel Angle to Patient Skin

Simulations have also been performed for different vein depth and bevel angles, see Figure 8.

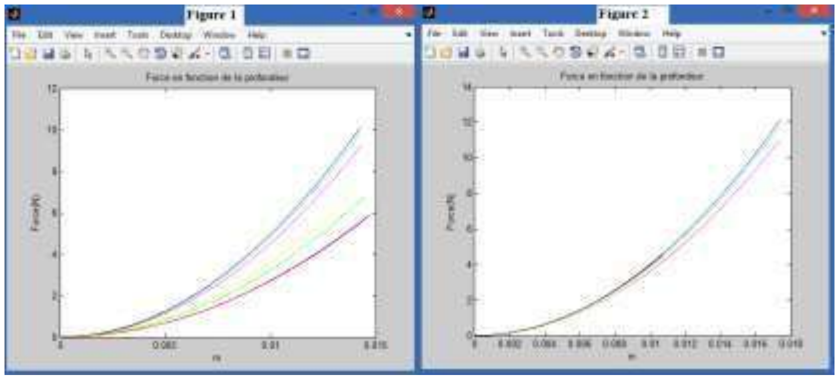

Figure 8: *Needle Applied Force vs Vein Depth for Different Bevel Angles (25°, 30°,35°,40°)*

During first phase of stinging, see Figure 8 left, the skin is deformed under needle pressure. The only force involved is the strength of needle tip. This phase ends when the needle penetrates skin tissue. In this simulation, the bevel angle remains constant for the 7 patients (30 °). Only the Young modulus that connects compression to deformation of the skin differs from one patient to another.

On Figure 8 right, the force curves are displayed in terms of needle insertion depth taking into account skin resistance. Depending on average Young modulus, a specific needle is selected and used with a different bevel. For high skin resistance it is necessary to use a needle with small bevel angle, and conversely a needle with a greater bevel angle is required for low skin resistance. Simulations indicate that increasing needle diameter and insertion velocity results in larger insertion force. Reduction of needle bevel angle results in a decrease of insertion force. Because of the different responses, it is interesting to adjust needle bevel to the resistance of patient skin, so that it is possible to always operate with constant speed, see Figure 9.

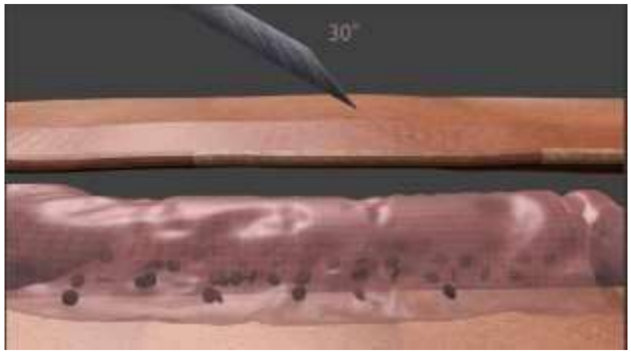

Figure 9: *Simulation of Needle Insertion*

This would provide a nearly constant insertion force for different types of skin, and thus considerably simplify automation procedure which can be monitored by fuzzy type control with simple membership functions based on previous results summarized in Figures 7- 8 and Table I below.

Table 1: *Influence of Parameters on Acting Forces*

	$f_{\text{stiffness}}$	$f_{\text{friction}} + f_{\text{cutting}}$	F_{total}	Empirical value
Needle Diameter	+	–	+	0,7 mm
Bevel Angle	+	–	+	[25°:40°]
Insertion Velocity	–	+	+	/
Young Modulus	+	–	+	skin

5. Conclusion

The aim of the project was to discuss elements for a solution to the control of interaction between a stiff object and a soft environment on specific application of needle insertion control. Such problem is still open because the physics of interaction is difficult to represent accurately enough, in order to remove the very contradictory requirement of monitoring a too precise output in a too soft environment. After collection of relevant data from expert medical personnel, a model taking into account skin viscoelasticity has been built up to describe needle-skin interactions during stinging process in order to evaluate to what extend needle insertion in a vein can be automatically performed.

These interactions are depending on several parameters which can be split into 3 categories: needle geometry, patient tissue characteristics and insertion methods. Analysis of last group showed weakness of previous studies modelling skin distortion only for normal penetration angle. In present case, best angle has been researched in the model by training a neural network to represent system complexity with different input parameters. With (modest) actual learning database, highest success rate is 70%. However, the results also suggest that it is possible to combine parameters action so that for most parameter range, insertion can be operated at constant speed, which largely simplifies automation of insertion process by fuzzy type controller.

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