This is the Pre-Published Version.
The following publication K. Choi, X. He, V. C. L. Chiang, Z. Deng and J. Qin, "A Heuristic Force Model for Haptic Simulation of Nasogastric Tube Insertion Using Fuzzy Logic," in IEEE Transactions on Haptics, vol. 9, no. 3, pp. 295-310, 1 July-Sept. 2016 is available at https://dx.doi.org/10.1109/TOH.2016.2550044

A heuristic force model for haptic simulation of nasogastric tube insertion using fuzzy logic

Kup-Sze Choi[1,2], Xue-Jian He[1], Vico C.L. Chiang[1,2], Zhaohong Deng[3], Jing Qin[1, 2]

[1]Centre for Smart Health, School of Nursing, Hong Kong Polytechnic University, Hong Kong
[2]School of Nursing, Hong Kong Polytechnic University, Hong Kong
[3]School of Digital Media, Jiangnan University, Wuxi, China

Abstract

Nasogastric tube (NGT) placement is an essential clinical skill. The training is conventionally performed on rubber mannequins albeit practical limitations. Computer simulation with haptic feedback can potentially offer a more realistic and accessible training method. However, the complex interactions between the tube and the nasogastric passage make it difficult to model the haptic feedback during NGT placement. In this paper, a fuzzy-logic-based approach is proposed to directly transfer the experience of clinicians in NGT placement into the simulation system. Based on their perception of the varying tactile sensation and the conditions during NGT placement, the membership functions and fuzzy rules are defined to develop the force model. Forces created using the model are then combined with friction forces to drive the haptic device and render the insertion forces in real time. A prototype simulator is developed based on the proposed force model and the implementation details are presented. The usability of the prototype is also evaluated by clinical teachers. The proposed methodology has the potential for developing computerized NGT placement training methods for clinical education. It is also applicable for simulation systems involving complicated force interactions or computation-expensive models.

Keywords: Fuzzy logic, Force modeling, Nasogastric tube placement, Haptic rendering

1. Introduction

Nasogastric tube (NGT) placement is an essential clinical procedure which involves the insertion of a plastic tube into the stomach for feeding or drainage. In the procedure, clinicians need to carefully insert the NGT through the nostril, nasal cavity, pharynx and esophagus, and finally reaching the stomach (see Fig. 1). Despite a common clinical operation, NGT placement has led to serious complications due to inadvertent misplacement or excessive insertion forces [1].

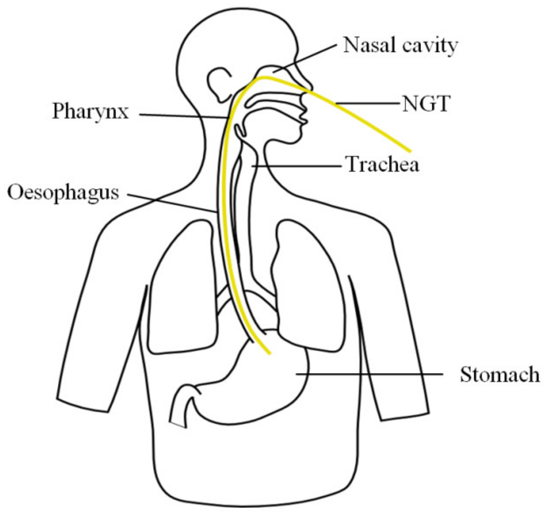


Fig. 1. Schematic diagram of NGT placement.

NGT placement is a blind process. Clinicians rely on the markings on the tube to estimate the position of the tube inside the body, and the kinesthetic feedback to determine the appropriate maneuver at different stages of the process. Conventionally, the training of NGT placement is performed on rubber mannequins. It has practical limitations, e.g. the mannequins do not replicate human anatomy and reproduce the tactile feeling in a realistic manner. In this regard, it is helpful if the training can be computerized to make it more realistic, and also available for clinical education. Here, haptic feedback is an essential component of the computer-based NGT placement simulation. However, due to the complicated interactions between the NGT and the nasogastric passage, simulating the forces during the insertion procedure presents a major challenge.

While physic-based simulation methods such as finite element method (FEM) and mass-spring system (MSS) have been successfully applied in many medical simulation applications [2, 3], it is non-trivial to employ these methods for NGT placement simulation considering the anatomical complexity of the nasogastric passage and the tube-passage interactions. Compared to other medical instruments, e.g. needle, catheter or trocar, NGT is more flexible in its operation that makes it more complicated to simulate the insertion. Besides, the computation also needs to be fast enough, at a refresh rate of 1 kHz, in order to simulate the haptic feedback in a smooth and natural way. Nevertheless, haptic simulation using computation-intensive methods like FEM can be achieved in real time with the better hardware available nowadays or using alternative approaches [4]. Despite the theoretical rigor, the physics-based approaches still require accurate identification of the model parameters for realistic simulation. In the case of NGT insertion, the identification is practically not straightforward as it is necessary to measure the in-vivo insertion forces under varying clinical conditions, e.g. the degree of lubrication, nasogastric anatomy, neck flexion angle and the insertion depth. Hence, the accuracy of the physics-based models would eventually be undermined by the unavailability of accurate model parameters.

Simplification of the computation in physics-based methods is also proposed. For example, a computation-efficient analytical model involving Coulomb friction force, viscous force and collision force has been developed to simulate the insertion of a catheter in nasotracheal suctioning [5]. The nasotracheal passage is also simplified as a cylindrical tube of constant radius and the pressure is evenly distributed along the tube. However, the setting of the model parameters and the realism of the simplified model remains a question.

Another possible approach is to adopt data-driven models. Data-driven models are not only computationally efficient for the real-time performance, but also suitable for handling complex simulation scenarios [6]. In the approach, the behavior of simulated objects is modeled based on the data measured on the real objects, or pre-computed offline using computational algorithms. Then, the offline data are used to generate the visual and kinesthetic responses of the simulated objects in real time. However, a large amount of data is usually required in this approach and the data may not be readily available, e.g. it is difficult to measure the insertion force data on patients in vivo during the NGT placement process. In our previous work [4], an offline simulation approach was adopted to obtain the relationship between the insertion depth and insertion force based on a non-linear FEM. The pre-computed data were then used to generate the forces in real-time simulation. However, in this approach it is difficult to consider other factors like the tube lubrication and the patient's neck flexion.

Given the difficulties in using the conventional methods to develop NGT insertion force model, alternative approaches are investigated in this paper. In practice, nurses are able to perform NGT placement properly based on their knowledge of the nasogastric anatomy, their previous intubation experience, and the *en route* tactile feeling. Leveraging the knowledge of clinical experts to develop the insertion force model empirically is deemed a viable approach. Hence, fuzzy logic system is investigated in attempt to directly capitalize the expert knowledge for the development of the force model. By taking advantage of the fuzzy systems, clinical experts can use linguistic terms to define the specific characteristics of the NGT placement process. Their knowledge and experience can then be used to develop the force model.

The rest of the paper is arranged as follows. First, the work related to the proposed fuzzy-logic-based force models is reviewed in Section 2. The fuzzy-logic-based force model proposed for simulating the forces during NGT placement is discussed in Section 3, followed by the haptic rendering method as explained in Section 4. The development and assessment of the prototype haptic simulation system for NGT placement is discussed in Section 5. Discussions and conclusions are presented in the last two sections respectively.

2. Related Work

Many efficient and stable haptic rendering approaches have been proposed, including god object [7], proxy [8], virtual coupling [9], multi-rate [10], voxel sampling [11], SQ-Map [12], etc. They are usually applied to the scenarios where simple or rigid tools are used. For the simulations of the interactions between thin deformable tools and soft tissues, e.g. simulations of catheter insertion, these methods are not directly applicable. Catheter insertion is usually assisted by a stiff yet flexible guide wire. Many physics-based models have been proposed for simulating the guide wires, for example, energy minimization [13] [14], finite beam element [15], mass-spring [16], and Cosserat elastic rod [17] [18]. However, since NGT is hollow, more flexible and thus easily bent, it is unclear if these physically based models could be directly applied to the simulation of NGT intubation. Furthermore, NGT insertion also involves ad-hoc clinical arrangements, e.g. tube lubrication, flexion of patient's neck and swallowing. Here, we explore the use of fuzzy-logic-based force models which can take multiple mechanical and clinical factors into consideration in the simulation. There has been a substantial amount of literature on the application of fuzzy logic for haptic rendering with robots [19-23], and on the prediction of forces in machining planning [24, 25]. A review of fuzzy-logic-based force models employed to simulate tissue response in the context of medical simulation is presented below.

An adaptive neural fuzzy inference system (ANFIS) was developed to model soft-tissue deformation [26], where the displacement of real tissues due to forces was tracked by optical markers using motion capture system. The force and position data of the central marker were used as the inputs of the ANFIS and the positions of the other markers as the outputs. A learning algorithm was used to tune the fuzzy sets using the measured data, whereas fuzzy logic was used to directly encode expert knowledge by using rules based on linguistic terms. The trained ANFIS achieved satisfactory results in estimating the marker trajectories.

Modeling of mass-spring-based soft-tissue deformation was also performed using neuro-fuzzy model [27, 28]. With a fuzzy system built using medical terms, knowledge of medical experts on soft tissue deformation was transferred into the simulation system to define the visual and haptic tissue response. In the model, the fuzzy-system was used to derive the parameters of the mass-spring network and thus the definition of the behavior of the simulated tissues. On the other hand, an artificial recurrent neural network was used to model the process of the simulation. With the neuro-fuzzy system, the simulator achieved a high level of realism.

Simulation of surgical cutting forces has also taken advantage of neural fuzzy modeling techniques. In a study, with cutting depth and velocity as the inputs of the model, and cutting force as the output, the parameters of the fuzzy sets were learned and optimized using a back-propagation algorithm [29]. The fuzzy haptic model achieved more realistic and smooth haptic display than conventional methods like hybrid models that combine finite element model and motion dynamics [30]. In a similar work where the inputs to the fuzzy system were the tissue stiffness and the forces exerted by users, and the output was the cutting depth [31], robust and real-time tissue cutting simulation was achieved and the results were consistent with the measured data. However, the fuzzy-logic-based method only captured the static cutting properties and did not sufficiently embody the transient. A hybrid model combining fuzzy logic and the Kelvin rheological model was then proposed [32], with the former used to model the multivariate and non-linear static properties of cutting and the latter for the transient effects. The model produced more realistic simulation than that using the Kelvin model or the fuzzy logic based model alone.

Fuzzy system has also been developed to map electromyogram (EMG) signals to the forces generated by human arm muscles [33, 34]. Three kinds of muscle behaviors were implemented with fuzzy logic, namely, passive force-length behavior, active force-length behavior, and force-velocity behavior. In the model, a neuro-fuzzy system was used to adapt the model with experimental data [33], whereas a genetic algorithm was used to identify the appropriate parameters of the membership functions [34]. The fuzzy system was robust against noise and was able to model the uncertainties in the muscle signals.

3. The Fuzzy-Logic-Based Force Model

As fuzzy systems have demonstrated promising potential for haptic force modeling, a fuzzy-logic-based approach is proposed in this paper for NGT placement simulation. The general idea of fuzzy systems is first presented here. A fuzzy inference system (FIS) uses fuzzy logic to map the given inputs to the outputs. A very common FIS is the Mamdani system [35]. It consists of three conceptual components: a rule base; a dictionary to define the membership functions; and a reasoning mechanism to perform the inference procedure based on the rules and derive an output. In general, six steps are involved to compute the output of the Mamdani FIS: 1) define a set of fuzzy rules; 2) fuzzify the inputs using the input membership functions; 3) combine the fuzzified inputs using the fuzzy rules to obtain the rule strength; 4) compute the consequences of the rules by combining the rule strength and the output membership function; 5) combine the consequences to get an output distribution; 6) defuzzify the output distribution to get a crisp output. This standard approach is adopted by the proposed NGT placement simulator. Instead of rigorous physical or mathematical formulation, the approach provides a simple yet effective means for modeling complex systems based on vague or inexact information. It relies on the empirical knowledge of users rather than the technical understanding of the systems [36], where the system behavior can be approximated when analytical or numerical solutions are not unavailable [37]. Hence, FIS is considered to be applicable for modeling the insertion forces in the NGT placement simulation. By consulting the clinical experience of experts in NGT placement, it is concluded that neck flexion angle (NFA), lubrication of NGT, insertion speed, and insertion depth (i.e. the position of tube inside the nasogastric passage) are the major factors determining the required insertion force, while other factors such as the diameter of the NGT and the body temperature are relatively minor or not relevant. These four parameters are therefore used as the inputs of the proposed fuzzy-logic-based force model, and the only output is the insertion force (see Fig. 2). Details of the four inputs will be further discussed in the following sub-sections.

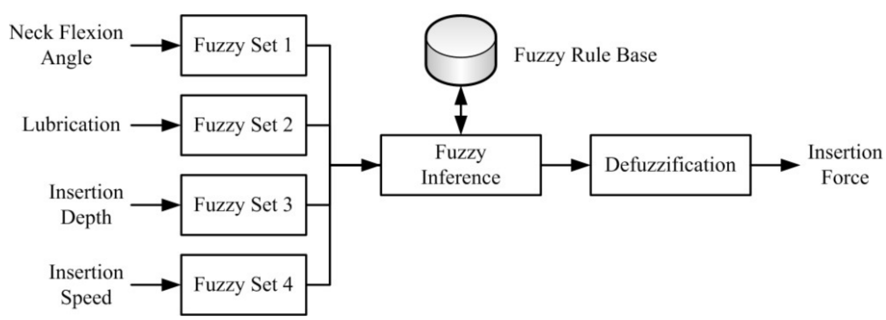


Fig. 2. Structure of the fuzzy-logic-based force model.

The crisp inputs are first fuzzified through the membership functions. They are then fed into the inference engine for evaluation based upon the fuzzy rule base. The outputs obtained from the inference engine are then defuzzified to get the final crisp output. To construct the fuzzy system for modeling the insertion forces, the fuzzy rules as well as the membership functions defining the fuzzy sets are iteratively adjusted by expert clinicians based on the difference between their experience and the simulation results [38]. The definition of the membership functions and the fuzzy rules are presented in Section 3.1 and 3.2 respectively. The mechanism of fuzzy inference and the proposed fuzzy-logic-based force model are discussed in Section 3.3 and Section 3.4.

3.1 Membership Functions

A fuzzy set is described by a membership function with values in the interval [0, 1]. It defines the degree of membership of a variable expressed with a linguistic term. The closer to unity the degree of membership is, the more the predicate is satisfied. In addition, a fuzzy set also defines the semantics of linguistic variables, where graphs are used to represent the degree of truth for each input. For the four-input-single-output system in the study, trapezoidal membership functions are used because they are the commonly used for FIS, and their shapes can be tuned in an intuitively and convenient way simply by adjusting the positions of the vertices (see Fig. 3) when compared other membership functions such as Gaussian functions.

Meanwhile, the input membership values are used as weighting factors by the fuzzy rules to determine their contributions to the fuzzy output sets. Typical membership function construction methods include polling, interval estimation, membership exemplification, pair-wise comparison, fuzzy clustering [39], neural fuzzy [40, 41] and organizing map [42]. In this study, polling and fuzzy clustering, commonly used in fuzzy modeling, are employed to construct membership functions. In the construction of the membership functions, expert nurses need to rate their level of agreement using questionnaires, the use of the polling approaches therefore fit naturally in the situations. Fuzzy clustering is favorable for the flexibility that a data point can be modeled to have a probability of belonging to two overlapping clusters.

3.1.1 Lubrication

In clinical practice, lubricant is applied to the exterior of the NGT to reduce the friction during insertion. In the proposed system, the degree of lubrication is defined within the range from 0 to 1, with 0 denoting the worst lubrication condition and 1 be the best. The membership functions of lubrication are shown in Fig. 3(a).

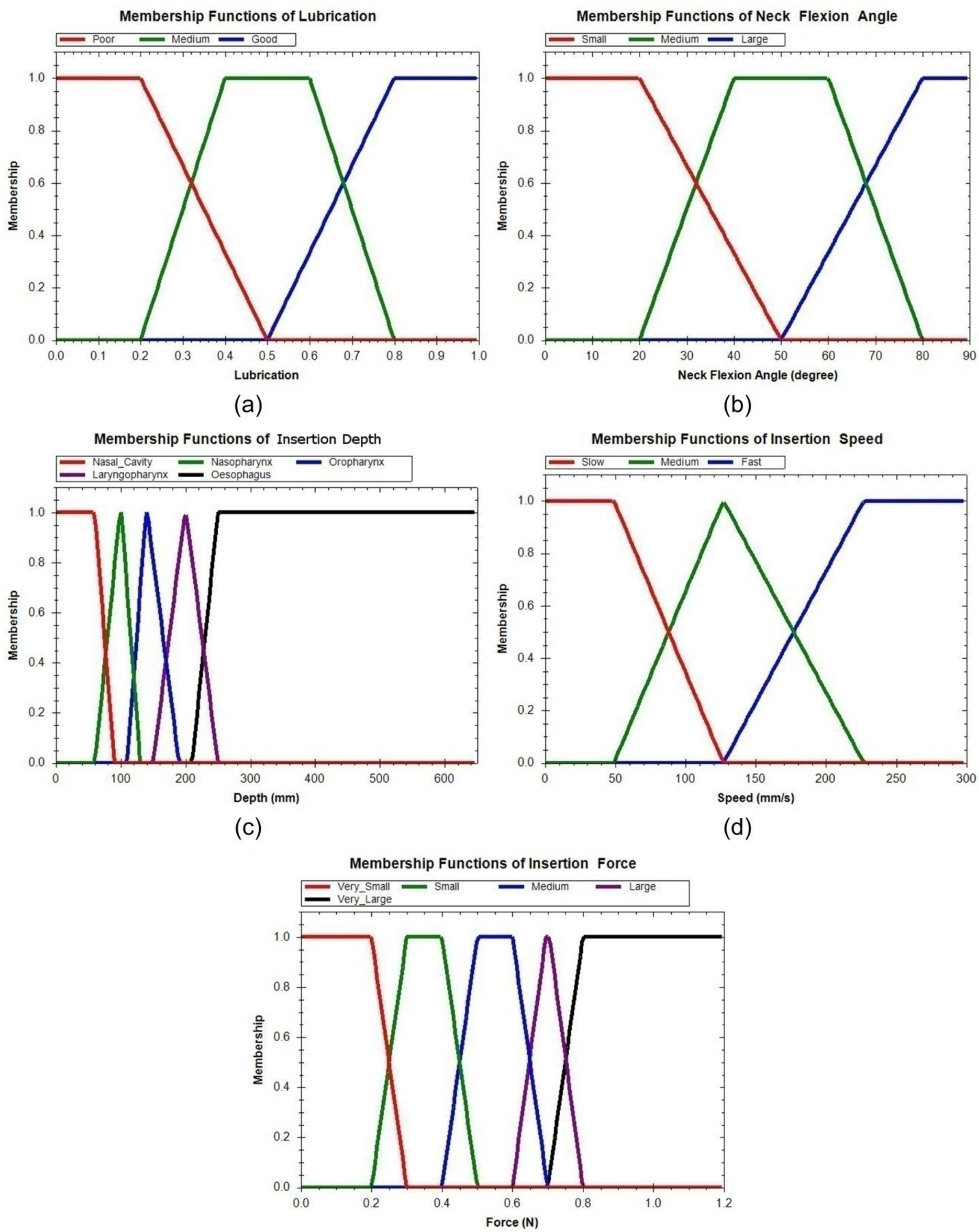


Fig. 3. Membership functions of (a) lubrication, (b) neck flexion angle, (c) insertion depth, (d) insertion speed, and (e) insertion force.

3.1.2 Neck Flexion Angle

NFA also plays an important role in determining the insertion force. Flexing the neck forward can prevent the tube from entering the trachea and facilitate smooth insertion [43]. Here, the angle is defined within the range from 0 to 90 degrees, with 0 degree referring to neutral upright position without flexion, and 90 degrees indicating the neck being fully flexed forward. The membership functions of NFA are shown in Fig. 3(b).

3.1.3 Insertion Depth

During NGT placement, clinicians are attentive to the specific locations along the nasogastric passage where large insertion forces may be perceived. These locations include pyriform sinuses and arytenoid cartilage [44], for example, which serves as haptic landmarks suggesting the current position of the tube during the blind placement process. It is therefore of clinical significance to estimate the location of the tube by referring to the anatomical structure that the tube has reached, rather than the length of tube that has been inserted into the nasogastric passage. Hence, the locations that the tip of the tube would reach are defined in terms of 5 concatenating anatomical regions, i.e. nasal cavity, nasopharynx, oropharynx, laryngopharynx and esophagus, based on the convention commonly adopted in practice by clinicians. The corresponding depths of the regions are obtained with reference to the Visible Human Project dataset [45]. The size of the sagittal image for the whole body is 1216×5164 pixels, with a resolution of 0.33 mm/pixel. The image of the upper part of the body is shown in Fig. 4. The blue curve represents an NGT fully inserted through the passage into the stomach and the 5 regions are marked using the red circles. Starting from the nose, the first curve segment between the first and the second red circles represents the section of the tube residing in the nasal cavity; the second curve segment residing in the nasopharynx; the third segment in the oropharynx; the fourth and the fifth in the laryngopharynx and the esophagus respectively; and the last segment in the stomach. The change of insertion force due to the section of the tube in the stomach is assumed to have negligible contribution to the overall insertion force. The membership functions of insertion depth along the passage are measured with reference to the image, as shown in Fig. 3 (c).

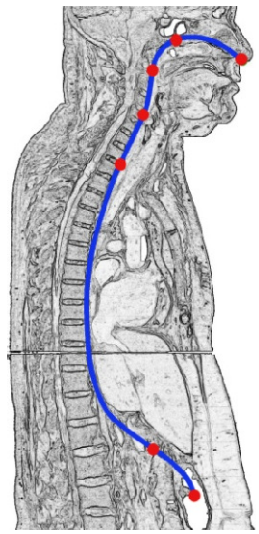


Fig. 4. Estimation of NGT insertion depth by making measurements on a sagittal image of the Visible Human dataset (The image displayed is down-sampled and adjusted to improve visibility).

3.1.4 Insertion Speed

From classical dynamics, the tube insertion force is related to the insertion speed by the characteristics of the system, e.g. damping and viscosity. In the study, the knowledge of experienced clinicians is capitalized to define the membership functions of the insertion speed experimentally. The experimental setup is shown in Fig. 5. The haptic device employed is the Geomagic Touch, with 6 degrees-of-freedom positional inputs and 3 degree-of-freedom force output.

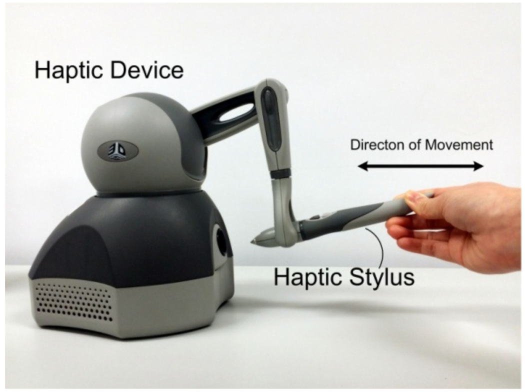


Fig. 5. The experimental setup for obtaining the membership functions of the insertion speed and insertion force.

Four advanced practice nurses were recruited as subjects (S1 to S4) to participate in the experiments. They are all registered nurses with more than 10 years of NGT placement experiences. The subjects are right-handed, with no haptic deficit and previous experience in using haptic devices. They were required to hold the stylus of the haptic device and move it horizontally to emulate insertion at three levels of speed as described by linguistic terms, i.e. slow, medium or fast, with one experiment for each speed level. They performed the action by referring to their previous experience, and by imagining as if they were inserting a real tube at a certain speed level, respectively, in the placement operation. At each speed level, the subjects performed the insertion consecutively four times. The recorded insertion speed for "fast insertion" is shown in Fig. 6. It is clear from the figures that the subjects had different perceptions of the insertion speed, with subject S4 performing relatively slower in all the experiments. The speed variation of subject S1 is larger than the other subjects, whereas the speed of S2 remains relatively more consistent. The statistical data of insertion speed are given in Table 1.

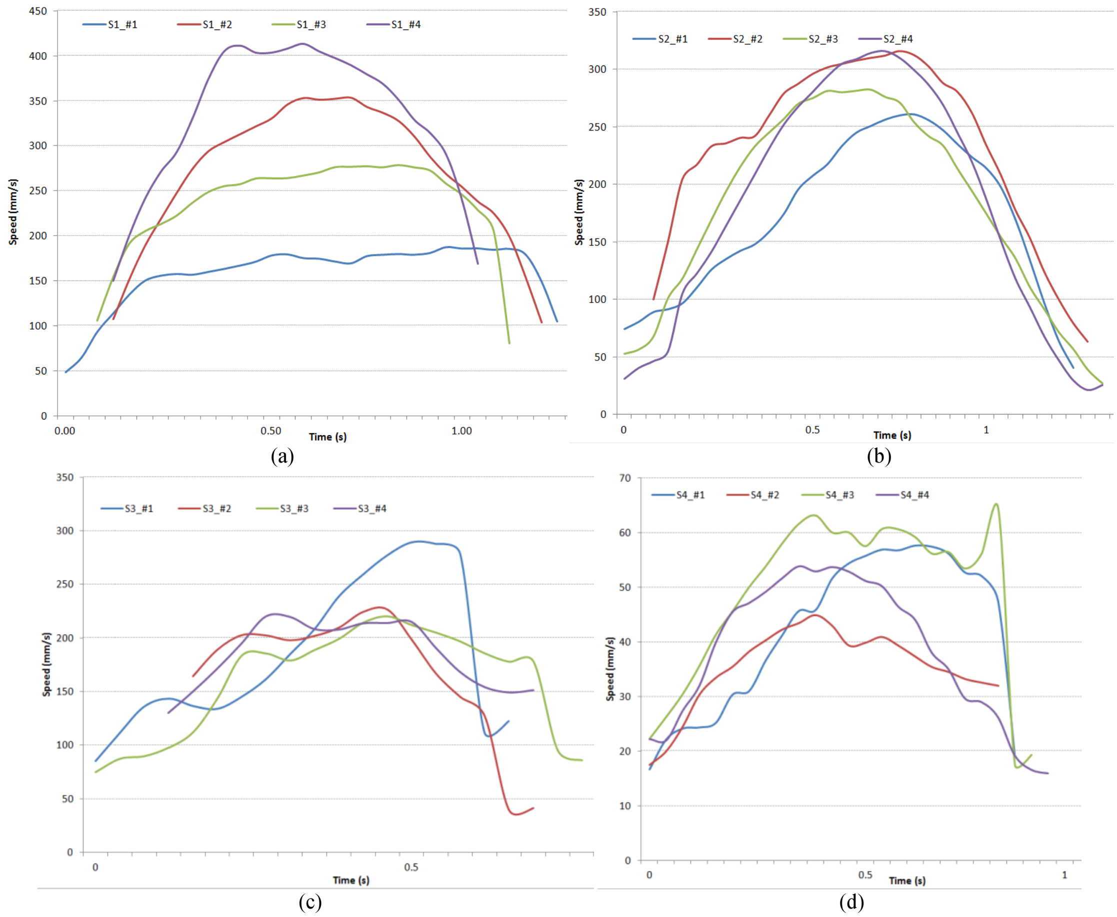


Fig. 6. Experiments of insertion speed at fast level for four subjects: (a) S1; (b) S2; (c) S3; (d) S4.

Table 1 Insertion speed (mm/s) of the three experiments.

Speed Level	Subject			
	S1	S2	S3	S4
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Slow	46.0 (17.1)	121.1 (35.7)	57.9 (18.1)	31.1 (8.9)
Medium	129.2 (40.1)	168.9 (61.6)	106.0 (25.0)	38.0 (13.8)
Fast	256.7 (102.1)	180.3 (92.4)	170.7 (55.0)	44.4 (18.7)

In this study, Fuzzy C-Means method (FCM) [46] is adopted to construct the membership functions of insertion speed by partitioning a finite number of data points into a collection of fuzzy clusters based on the objective function J as follows,

$$J = \sum_{i=1}^{n} \sum_{k=1}^{c} \mu_{i,k}^{m} \, |P_i - V_k|^2 \,, \qquad (1)$$

where n is the number of elements, c is the number of clusters, μ is the fuzzy membership degree, m is a fuzziness factor (a value > 1), $\boldsymbol{P}_i$ is the i^{th} element value, $\boldsymbol{V}_k$ is the centroid of the k^{th} cluster, and $|P_i - V_k|$ is the Euclidean distance between $\boldsymbol{P}_i$ and $\boldsymbol{V}_k$. The data from the experiments were fed into the FCM, where the degree of membership of each data point to each cluster center was calculated by the distance between the cluster center and the data point. Fig. 7 shows the clustering results for the four subjects. The results indicate that the center points with membership value 1 and the end points with value 0 can be obtained as shown in Fig. 8. The trapezoidal membership functions are then constructed by averaging, as shown in Fig. 3(d).

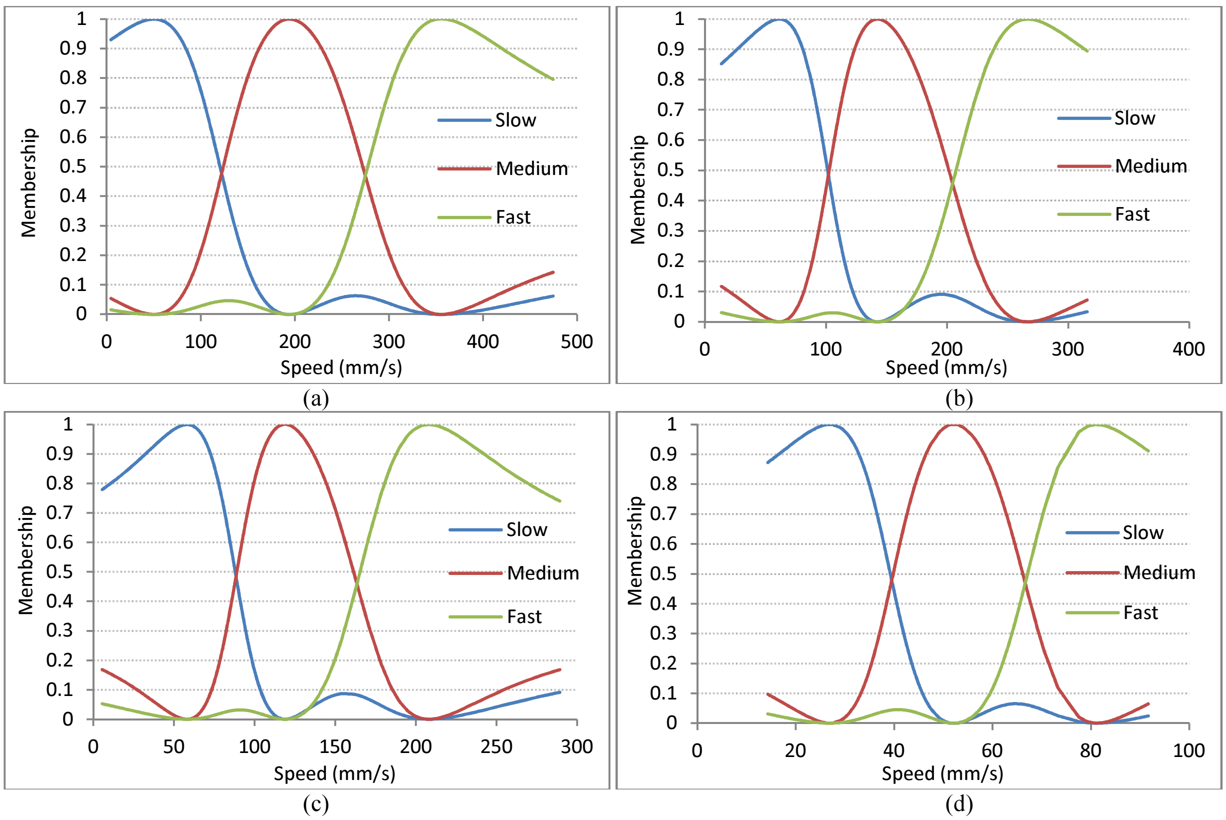


Fig. 7. Clustering of insertion speeds using FCM for the four subjects: (a) S1, (b) S2, (c) S3 and (d) S4.

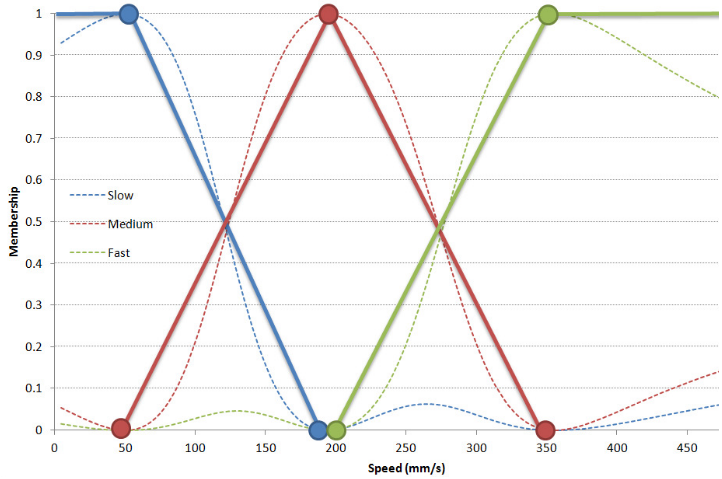


Fig. 8. Membership functions constructed from the results of FCM.

3.1.5 Insertion Force

The membership functions of the insertion force are also defined experimentally based on the experience of the four subjects. The same experiment setup shown in Fig. 5 was adopted. In the experiments, the subjects were asked to hold the stylus of the haptic device horizontally, where a force was pushing against the participants via the stylus. The pushing force was increased from 0.1 N to 1.7 N with an increment of 0.1 N per step. In each step, the subject was asked to feel the pushing force by moving the stylus horizontally forward, and then indicate the magnitude of the force based on their previous experience in real NGT placement using one of the five linguistic terms, “Very Small”, “Small”, “Medium”, “Large” and “Very Large”.

The results of the force perception experiment are given in Table 2. It is found that a force of magnitude 1.1 N is the upper bound of insertion force experienced by the subjects in real NGT placement operations. A voting mechanism was used to map the forces of different magnitudes to the corresponding linguistic terms. For example, two subjects agreed that a force of 0.2 N was “Very Small”, while the same force magnitude was considered to be “Small” and “Medium” respectively by the other subjects. The voting system was defined such that a candidate won by obtaining half of the votes or more. Therefore, 0.2 N was classified as a “Very Small” force with 2 out of the 4 subjects voted for it. However, a tie might occur, e.g. all the subjects had different views on the strength of a force of 0.3 N. In that case, since the force in the experiment was monotonically increasing at each step, the linguistic term describing the next higher level of strength would be chosen. Hence, in the example given above, 0.3N was classified as "Small". Based on this voting mechanism, the membership functions of insertion force were constructed, which is shown in Fig. 3(e).

Table 2 Perception of NGT insertion force by the subjects.

Force (N)	Linguistic terms chosen to describe the strength of the force				
	Very Small	Small	Medium	Large	Very Large
0.1	3	1	0	0	0
0.2	2	1	1	0	0
0.3	1	1	1	1	0
0.4	0	2	1	0	1
0.5	0	0	2	1	1
0.6	0	0	2	1	1
0.7	0	0	1	2	1
0.8	0	0	1	1	2
0.9	0	0	0	2	2
1.0	0	0	0	1	3
1.1	0	0	0	0	4

3.2 Fuzzy Rule Base

The fuzzy rule base is composed of a set of linguistic rules that are obtained based upon the knowledge of experts. They are in the form of the "IF-THEN" rules. A questionnaire was designed for constructing the fuzzy rule base of the proposed system by exploiting the knowledge of the subjects in NGT placement. The linguistic variables used in the fuzzy logic system were explained to make clear their specific meaning. A diagram showing the larynx and the surrounding anatomic structures was also attached as a reference for the subjects to better relate the position of the NGT with respect to the overall nasogastric passage. The questionnaire contained 45 items, each describing a certain condition during NGT placement (IF part) and asking the subject to indicate the strength of the insertion force under such condition (THEN part). According to the experience of individual subject, a rule can be added to or removed from the rule base using a simple fuzzy rule editor provided by the system, which will be described in

Section 5. The questionnaire and the fuzzy rules defined based on the knowledge of subject S4 are shown respectively in Table A1 and Table A2 of the Appendix.

3.3 Fuzzy Inference

Fuzzy inference is a procedure for deriving conclusions from a set of fuzzy rules [47]. Once all the crisp inputs, i.e. tube lubrication, neck flexion angle, insertion depth and insertion speed, have been fuzzified into the corresponding linguistic values, according to the fuzzy rule base, the inference engine derives values for the linguistic variables. The two main steps in this process are *aggregation* and *composition*, referring to the computation of the values of the IF (antecedent) part of the rules, and the values of the THEN (consequent) part respectively. In the aggregation step, the degree of truth for each input in the IF part is calculated as the antecedent values, based on the degree of membership of the corresponding linguistic term. In the composition step, the results of the antecedent evaluation are applied to the membership function of the consequent (insertion force) by using clipping or scaling [48]. Then, the membership functions of all the rule consequents previously clipped or scaled are combined to form a single fuzzy set. When the single output fuzzy set is derived, the defuzzifier generates the final crisp values from the output linguistic values, via defuzzification by computing the "fuzzy centroid" of the area of the output fuzzy set.

3.4 The Generalized Force Model

The force model developed based on the approach described above is largely dependent on the definition of the fuzzy rules by individual subjects. Each subject tuned the membership functions and modified the fuzzy rules iteratively until a force model that can produce a tactile feeling in agreement with that in the previous NGT placement was obtained. Since variations in the experience of the subjects can yield different rules and thus leading to differences in the insertion force generated by the models, the contribution of the insertion force due to individual subjects, as obtained from the corresponding force models, are averaged to obtain the generalized simulated insertion force. In the generalized model, the insertion force $\boldsymbol{F}$ is calculated by:

$$F(v, d, l, a) = \frac{1}{N} \sum_{i=0}^{N-1} F_i(\boldsymbol{R}_i), \qquad (2)$$

where v is the insertion speed, d is the insertion depth, l is the degree of lubrication, and a is the neck flexion angle, F_i is the force model derived from the rule set $\boldsymbol{R}_i$ of the i^{th} subject. Here, it is assumed that that the insertion force model is developed with expert clinicians and their level of experience is similar such that the model can be obtained by averaging over the individual models. As the goal is to develop a realistic insertion force model, it is necessary to recruit expert nurses with as much experience as possible for building the model. In the study, all the subjects have more than 10 years of experience in NGT placement and they are considered very experienced.

The generalized force model gives the amount of insertion force as a function of the degree of lubrication, neck flexion angle, insertion speed and depth. The relationships between the insertion force and the four inputs can be studied graphically using a surface plot. Fig. 9 shows the force-speed-depth relationship when the degree of lubrication is 1 and the neck flexion angle is 45°. Furthermore, the relationships between the force and depth under different conditions can also be visualized. The effect of lubrication when the neck flexion angle is 90° and the insertion speed is 30 mm/s as shown in Fig. 10(a); the effect of neck flexion angle when the degree of lubrication is 1 and insertion speed is 30 mm/s in Fig. 10(b); and the effect of insertion speed when the degree of lubrication is 1 and the neck flexion angle is 90° in Fig.

10(c). It can be seen from these figures that the generalized model can simulate the reduction of insertion force when lubrication is applied; the increase in insertion force when the neck is not flexed, i.e. when the neck flexion angle is 0°; as well as the increase in insertion force with insertion speed. The simulated results are consistent with the experience described by the subjects.

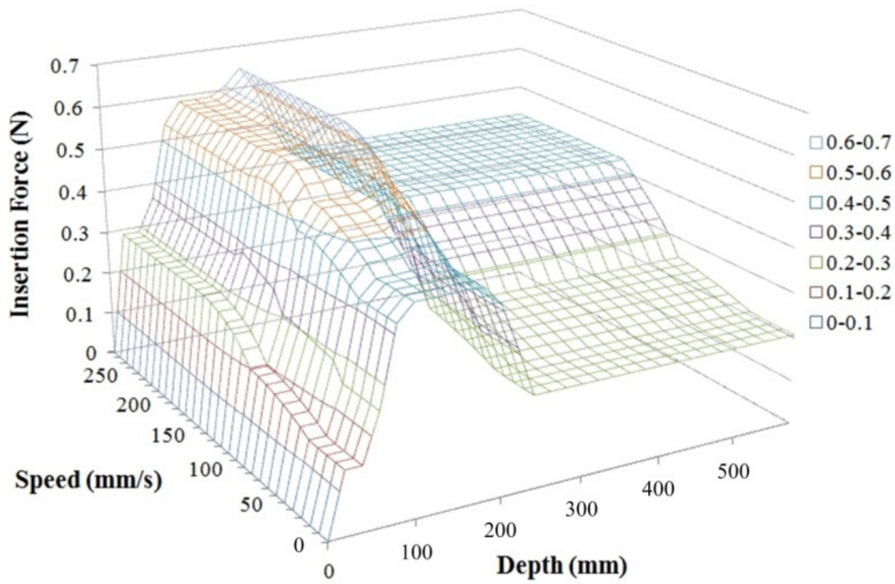


Fig. 9. 3D surface plot of the force-depth-speed relationship of the proposed fuzzy-logic-based model (lubrication = 1 and neck angle =45 degrees).

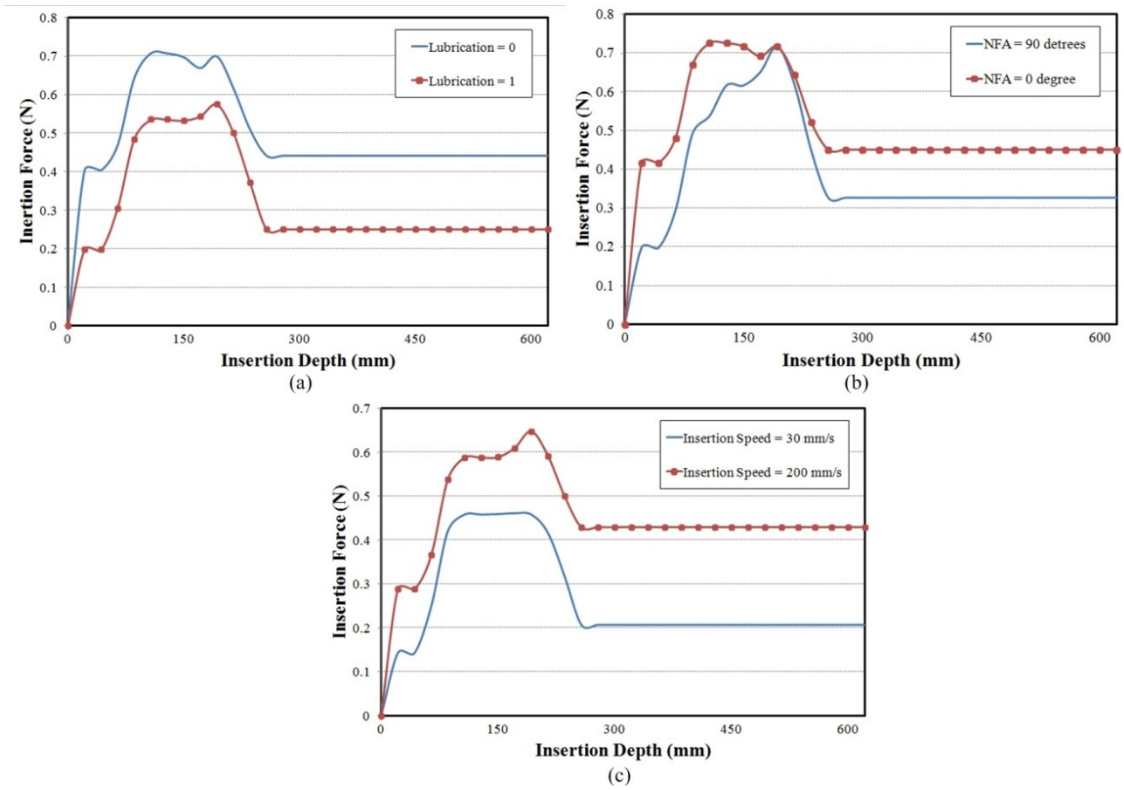


Fig. 10. The effect of (a) lubrication, (b) neck flexion angle and (c) insertion speed on the relationship between the insertion force and insertion depth (the settings are in the main text).

To investigate the extent of variation of the force model, the fuzzy-logic based force models derived respectively from the experience of the individual four nursing experts are compared. Under the same parameter setting, the 2D force-depth curves of the four models are plotted and shown in Fig. 11. It can be seen that the force profiles and trends are quite similar. Initially the forces rise when the NGT collides with the passages of the nasal cavity and then drop slightly. After the NGT reaches nasopharynx, the forces increase again and peak in the passage of oropharynx, while the peak value for S2 is relatively higher. The force magnitudes of all the four subjects are close after the NGT enters the esophagus. In the final model, the curves are obtained by averaging the forces of the individual models.

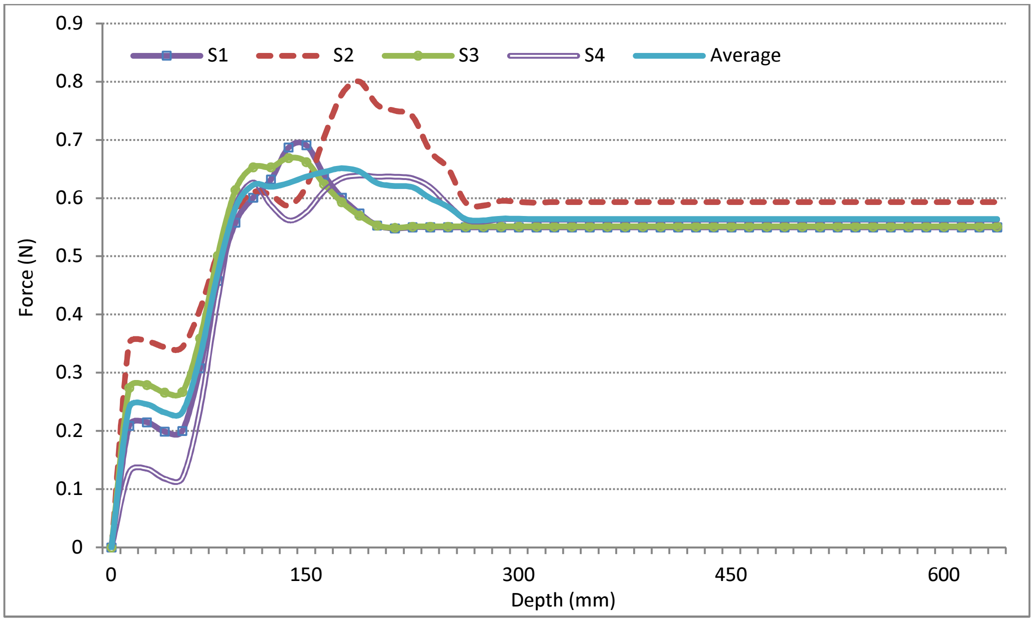


Fig. 11. Force-depth curves exported from the force models based on different fuzzy rules of four subjects with the same membership functions. The insertion speed is set to 50 mm/s; NGT lubrication level is 1.0; neck flexion angle is 60°.

3.5 Comparison with Physics-based Model

The method proposed here is compared with a physics-based model developed based on nonlinear FEM [4], where the insertion forces of a tube being inserted from the nostril to the laryngopharynx at a constant speed is simulated offline, and the wall of the passage is modeled as rigid body. In Fig. 12, the forces generated from this approach are compared with that from the proposed fuzzy-logic based method. For the fuzzy-logic based model, it can be seen that the force increases quickly before it reaches the wall of nasopharynx at a depth of about 22 mm. The force then decreases slightly. This phenomenon agrees with the experience of the nurses.

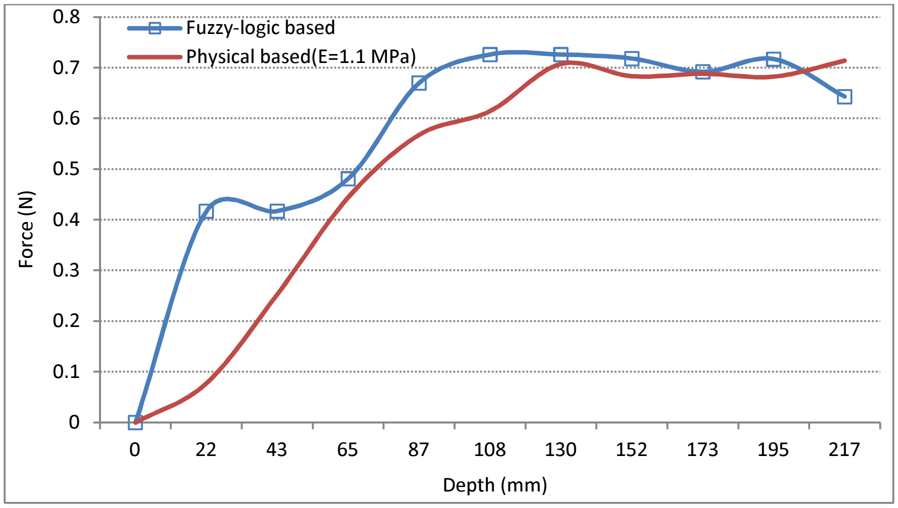


Fig. 12. Comparison between the proposed fuzzy-logic based approach and physics-based method.

4. Haptic Rendering

The fuzzy-logic-based model discussed in the last section simulates the insertion force *en route* when the NGT is continuously inserted along the nasogastric passage to the stomach. In practice, the tube is instead inserted stroke by stroke, advancing through the nostril into the body by a certain length at each stroke, until reaching the stomach. Hence, it is necessary to model the static and dynamic friction during the process, i.e., the friction forces arise from the situations when an insertion force is applied but yet to advance the tube (i.e. static friction), and when the force is large enough to counteract the friction and move the tube (i.e. dynamic friction). When the tube moves, the insertion force is governed by the proposed fuzzy-logic-based force model. The modeling of the friction forces during NGT placement is explained in Section 4.1 and the incorporation of the fuzzy-logic-based force model is presented in Section 4.2.

4.1 Friction Forces

When a force is applied to the NGT, before tube advancement can actually take place, static friction is created by the adhesive force between the tube and the surrounding tissues along the nasogastric passage to resist the tube from being inserted into the body. Under this situation, the relative velocity between the NGT and the tissues in contact is very small and close to zero. The static friction F_s is given by,

$$F_s = kX - \mu V, \quad (3)$$

where k is a coefficient depending on the tube-passage contact conditions; X is the displacement of the NGT in the passage, μ is a damping factor, and V is the speed of insertion. As the tube is pushed harder, the static friction caused by adhesion becomes larger. When the insertion force exceeds a threshold value F_m, the stick-slip phenomenon occurs and the tube begins to experience dynamic friction F_d which is smaller than F_s. The relation between the maximum static friction force and the dynamic friction force is: $F_m = (1 + \tau)F_d$, where τ is a constant. Beyond this point, the tube can be inserted more readily as the friction force drops slightly to F_d. According to the conventional Coulomb force model, the dynamic friction remains relatively constant. However, it does not apply to NGT placement because the contact conditions vary along the nasogastric passage. In this paper, the dynamic friction is instead modeled using the force data pre-computed with the fuzzy-logic-based force model presented in Section 3. The modeling of the static and dynamic friction during an insertion stroke is depicted schematically in Fig. 13.

The friction force model proposed here is similar to those developed for the simulation of needle insertion [49]. In both cases, before the needle (or the NGT) begins to slide, the interactions between the advancing needle (or tube) and the soft tissues result in surface deformation and large displacement of the tissues, which also creates friction forces. Once sliding occurs, dynamic friction comes into play, which, in the case of NGT insertion, is given by the proposed fuzzy-logic-based force model.

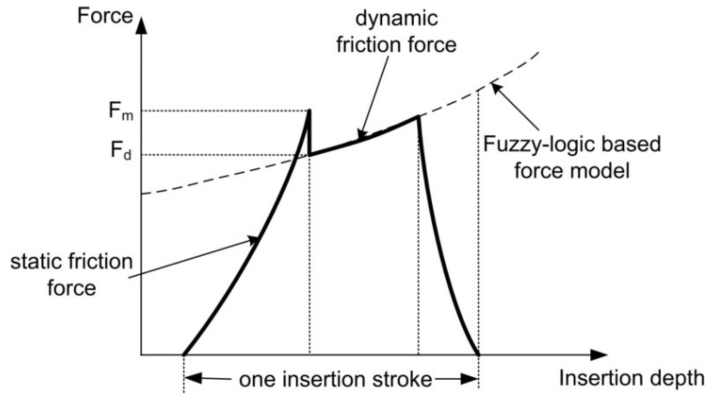


Fig. 13. Static and dynamic friction during an insertion stroke.

4.2 Force Rendering

Refer to the force rendering process shown in Fig. 14, after the construction of the FIS as described in Section 3, the four inputs – lubrication, NFA, insertion depth and speed – are then fed into the system. In the FIS, the inputs are first fuzzified using the input membership functions. The system then combines the fuzzified inputs using the fuzzy rules to generate the rule strength, and the output membership functions are used to compute the rule consequences. Next, all the rule consequences are assembled to produce an output distribution which is defuzzified to yield the crisp output, i.e. the insertion force. Finally, the insertion force obtained from the FIS is integrated with the force computed by the static friction force model (see Fig. 13 and Equation (3)) to generate the final feedback force to be felt by the hand of the user through the haptic stylus.

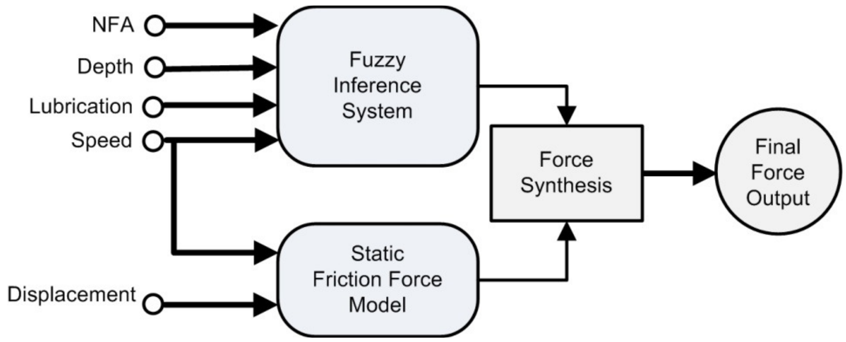


Fig. 14. Block diagram of force composition of the NGT placement simulation.

5. Haptic Simulation System

Based on the proposed fuzzy-logic-based force model, a prototype system is developed to simulate the haptic feedback during NGT placement. Details of the system are presented in this section, including model tuning, prototype system and assessment.

5.1 System Overview

The framework of the fuzzy-logic-based haptic simulation system for NGT placement is shown in Fig. 15. It contains individual modules for 3D scene visualization, graphical user interface (GUI) and force computation. In graphics rendering, geometrical models of the head of the patient, the hand of the user, and the NGT are visualized using OpenGL. In haptic rendering, the NGT insertion force is calculated based on the fuzzy-logic-based force model and the friction force model mentioned in the previous sections. The computed force is then transferred to the haptic rendering module to drive the haptic device at the refresh rate of 1 kHz using the OpenHaptics Toolkit. The GUI module provides users with the guidelines of NGT placement and the real-time information about the simulated placement, e.g. the temporal insertion force and the position of the NGT inside the body. The 3D graphics rendering module and the haptic rendering module are implemented with C++ programming language, whereas the GUI is programmed with C#. The communication between haptic and simulation modules is based on named pipes, where TCP/IP socket protocol is utilized for inter-module communications. Finally, that data that can be used to evaluate the performance of the users, e.g. NGT position, insertion speed, insertion force and completion time, are logged and recorded in a database.

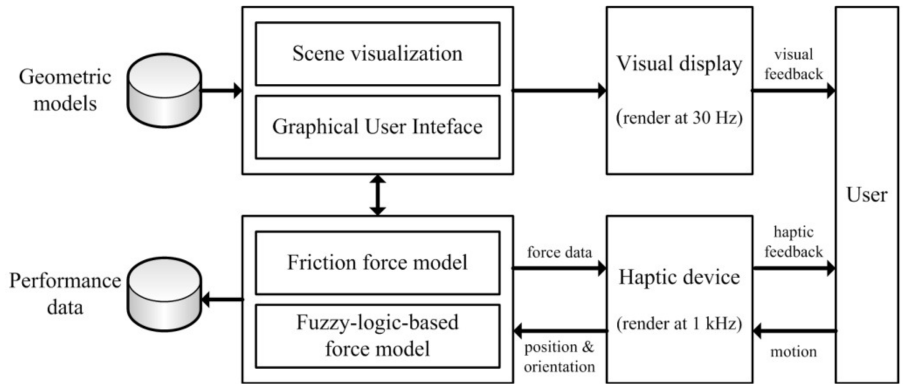
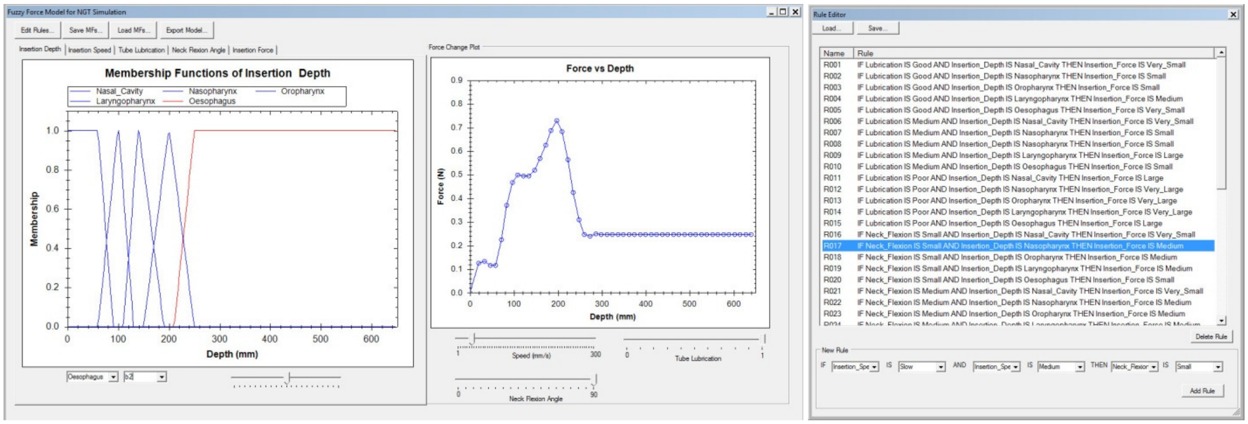


Fig. 15. Framework of the prototype NGT placement simulator.

5.2 Model Tuning

For the proposed fuzzy-logic-based model, as it is necessary to adjust the shape of the membership functions and the fuzzy rules manually and iteratively, an editor is developed in the GUI module of the simulation system to facilitate the adjustment. Fig. 16(a) shows the screenshot of the editor. User can manually edit the shape of the membership functions by adjusting the control points using a scroll bar. The insertion force computed with the fuzzy-logic-based model is updated in real time in response to the changes in shape of the membership functions. The GUI for editing the fuzzy rules is shown in Fig. 16(b). User can add or remove the fuzzy rules using the GUI. After the adjustments are made, the fuzzy-logic-based model can be exported for use in the haptic simulation system to render the insertion force of NGT placement.



(a) (b)

Fig. 16. Screenshots of GUI for adjusting (a) the membership function and (b) fuzzy rule base of the proposed fuzzy-logic-based force model.

5.3 Prototype System

5.3.1 Hardware User Interface

The fuzzy-logic-based haptic simulation system for NGT placement is implemented on a computer with an Intel Core i7-4712HQ (2.30 GHz) processor and 4 GB RAM, running Microsoft Windows 7 as the operating system. The simulator is equipped with a 3D-printed surface model of human head as shown in top of Fig. 17. The posterior part of the head model is cut away to allow space for mounting the haptic device. To provide a user interface with the look-and-feel similar to a real NGT, the original stylus is replaced with a soft plastic tube, where a micro-switch is put inside the tube, as shown the in the bottom of Fig. 17. The micro-switch can be actuated by pressing the wall of the plastic tube to generate a signal to the simulator via the adaptor connected to the haptic device. The signal is used by the virtual environment to invoke the simulation of the action of grabbing the virtual tube. The customized tubular user interface is inserted through the nostril of the 3D-printed head model from the back to allow user to move it from the front (top right of Fig. 17). The 3D hand model in the virtual environment is maneuvered using the customized interface. The virtual tube is grabbed when it is touched by the virtual hand and the micro-switch is pressed. With the tube grabbed, it can then be moved and inserted into the nostril. The virtual environment is synchronized and updated according to the maneuver of the tubular user interface. In the meantime, the corresponding insertion force is computed and sent to the haptic device. The feedback forces are rendered and transferred to the user's hand. At the end of an insertion stroke, the tube and the micro-switch are released, and the haptic stylus naturally returns to the start position under gravity. The next insertion stroke can be then performed in the same way. The force recorded in a simulated NGT placement training using the system is shown in Fig. 18.

Fig. 17. The setup of the proposed simulation system.

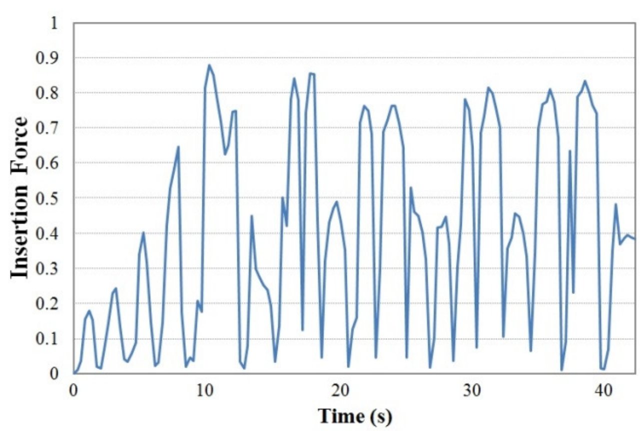


Fig. 18. Insertion force recorded in real time during the course of placement.

5.3.2 GUI and Virtual Environment

The GUI of the prototype system consists of two main parts: (1) 2D representation of visual cues to assist the users to perform NGT placement, including instructional texts describing the steps of the NGT placement procedure, a schematic diagram indicating the real-time position of the tube inside the body, an a real-time graph showing the insertion force being applied during the course of placement; (2) 3D representation of the patient, the NGT and the user's hand in the virtual environment, where the side view and front view of the virtual patient's head with the tube being inserted are rendered interactively in real time. The GUI of the system is shown in Fig. 19.

When the tube is being inserted into the virtual patent in the 3D environment, the corresponding position of the tube inside the nasogastric passage is displayed interactively in the 2D GUI, emulating the visual images of chest radiography that is used clinically for locating the NGT inside the body. Furthermore, nurse-patient interaction is also simulated such that when the NGT approaches the resistive pharyngeal region, the user can press a button in the 2D GUI to "instruct" the virtual patient to flex his neck to facilitate tube insertion in that region. The action of neck flexing is animated interactively in the 3D virtual environment.

Fig. 19. GUI of the NGT placement simulator: (from left to right) instructional text; schematic diagram showing the position of NGT inside the body, with real-time plot of insertion force applied displayed below; front view and side view of virtual patient.

5.4 Usability Evaluation

Nine clinical teachers were invited to evaluate the usability of the prototype and the applicability for NGT placement training. They were all experienced in teaching NGT placement. Four of them have over 16 years of experience, and three with 7 to 9 years. All the participants are right-handed, with neither haptic deficit nor previous experience in using haptic devices. A questionnaire of six items was designed for the participants to rate the usability of the simulator and to collect their comments [50]. A 7-point Likert scale (with 1 indicating "strongly disagree" to 7 indicating "strongly agree") was adopted. The items are listed as follows:

Q1. The procedure of the simulator is clear.
Q2. The graphical display of the simulator is realistic.
Q3. The insertion forces of the simulator are realistic.
Q4. The simulation experience will help learners to better perform NGT insertion with the real patients.
Q5. The simulator can be used to substitute the use of standard mannequin for NGT insertion training.
Q6. The simulator can be used in nursing curriculum to assist NGT insertion training.

The results are shown in Table 3. The participants tended to agree that the procedures simulated were clear (Q1) and that the simulator was of educational value for clinical teaching (Q4 and Q6), where the average score of the corresponding three items was greater than 5. For the other three items (Q2, Q3 and Q5), the average score was between 4 and 5. Regarding the quality of the graphical display (Q2), it was suggested that the procedure estimating the tube insertion length before the placement could be simulated, i.e., requiring the trainee to put the virtual tube from the nose tip to the ear lope and then the xiphoid of the virtual patient. Furthermore, in addition to the resistive intubation forces, the simulation of facial expressions and body movements of the virtual patient was recommended for they are important cues to suggest the trainee to adjust the ways of placement during the procedure. The participants found that the simulated forces were quite realistic. However, moderate scores were only given to item Q3, which was indeed largely due to the need to press the micro-switch inside the plastic tube. The participants opined that such action was not counter-intuitive and affected their perception in feeling the forces. Besides, the participants considered that, despite the inability of simulating the real anatomy and the insertion forces, the use of rubber mannequin remained a useful tool for experiential learning of NGT placement (Q5). Nevertheless, they agreed that the virtual NGT simulator was a complementary and helpful approach to mannequin-based teaching, as reflected by their favorable responses in items Q4 and Q6.

Table 3 Results of usability evaluation by the subjects.

Question	Mean	S.D.	Min	Max
1	5.78	0.83	5	7
2	4.89	1.17	3	7
3	4.44	0.88	3	7
4	5.22	0.97	4	7
5	4.89	1.54	3	7
6	5.44	1.24	3	7

6. Discussions

The paper proposes a force model to simulate the insertion force during NGT placement. Instead of modeling the interactions with physics-based approaches or attempting to obtain the actual force data by measurement, the proposed method directly capitalizes the knowledge of experienced clinicians using a fuzzy-logic-based approach to derive the insertion force. Nurses and clinical teachers have been recruited to evaluate the prototype system. They find that the tactile feeling generated by the proposed force model is similar to their experience in real NGT insertion, and consider that the haptic simulation system could be a useful training tool to complement the existing pedagogical approaches in clinical education.

The proposed force model is developed with the settings determined by trial-and-error adjustment. While the membership functions of insertion speed, depth and force can be obtained by clustering or averaging, interactive manual tuning of the functions is also required. In this tuning process, the positions of the control points of the membership functions are adjusted manually in order to yield an optimal mapping with the linguistic terms or output values. This is not straightforward and indeed counter-intuitive to the clinicians. Repetitive adjustments are needed to obtain a force model that can satisfactorily reflect the experience of the clinicians. The tedium of the tuning process may adversely affect the effectiveness of the transfer of expert knowledge to the fuzzy-logic-based force model.

It can be seen from Fig. 9 that, since the force-depth curves are relatively flat, the fuzzy-logic-based model cannot reflect the subtle changes in insertion force along the esophagus. This is because the membership functions of insertion depth that correspond to the region of esophagus have low resolution in the input space. The modeling of insertion force may be improved by using fuzzy rules with linguistic terms to allow clinicians to directly refer to their previous experience of force changes when the NGT is being inserted into the esophagus. However, it may also be difficult for them to relate the fuzzy rules to their experience, and thus introduce errors into the model. A more straightforward solution is to divide the section of esophagus in the nasogastric passage into several segments so that the resolution of the membership functions could be increased, at the expense of complexity due to the ensuing increase in the number of fuzzy rules.

Trapezoidal membership functions are used in the study to develop the fuzzy-logic-based force model. Other types of functions such as Gaussian functions could also be adopted. The effect of the shape of membership functions on the performance of the force model will be investigated to identify an optimal configuration that can realistically reproduce the tactile feeling of the clinicians during real NGT placement.

In the proposed approach, the insertion force and the static friction force are modeled separately, with the former simulated based on the fuzzy system to obtain offline insertion force data and the latter computed analytically in real time. The two forces are not modeled simultaneously by the fuzzy system since it is considered difficult for users to differentiate the two types of forces. It is also not intuitive for them to describe the extent of static friction using linguistic terms.

The fuzzy-logic-based force model presented in the paper is developed based upon the knowledge of four experienced clinicians who were all very experienced in NGT placement. To further improve the representativeness of the force model, more subjects with solid experience in NGT placement will be recruited. The model can indeed be continuously optimized with contributions from more experienced clinicians. The ultimate model established can then serve as the benchmark for training novice clinicians.

The realism of the proposed simulator is assessed by experienced clinical teachers. Quantitative assessment of the accuracy would require the physical measurement of the in-vivo insertion forces on human subjects, which is technically difficult and could lead to ethical concerns. Besides, special sensors and delicate customization are needed to modify the NGT for insertion force measurement. Alternatively, the forces might be estimated indirectly using advanced medical equipment like high-resolution esophageal manometry, which is a device used to measure the pressure during swallowing and evaluate the esophageal motility for the diagnosis of digestive diseases. Given the difference in texture and flexibility, the estimation does not necessarily represent the real NGT insertion forces. Consider that such equipment is not available for the present study and obtaining research ethical approval from hospitals as well as consents from patients could be an issue, the realism of the proposed simulator is only evaluated through subjective evaluation by experienced clinicians. In clinical education, the competence of NGT placement, indeed, is evaluated by examiners who make observations on the performance of the trainees and grade using a checklist.

In the proposed model, different fuzzy rules are pre-set and then selected by individual subjects based on their knowledge and experience. The models developed for each of the subjects are averaged to yield the generalized forced model by assuming that the subjects are all equally and very experienced. Otherwise, if the modeling is resorted to intermediates due to unavailability of experts, which is not desirable, it is then necessary to assign an appropriate weight for each individual model according to the level of experience of the subject and compute the weighted average. NGT insertion is a clinical skill depending on the interplay of competencies in dexterous skill, guidance given to the patient to cooperate, and other clinical conditions. The more the NGT placement experience, the better the competency. Therefore, experience can be chosen as a weighting factor in the model. The level of experience can be expressed quantitatively with the number of years of experience, or identified categorically by classifying the subjects into discrete groups, e.g. beginners, intermediates and expert. However, the relationship between weighting and experience level is not straightforward. Data of real insertion forces are probably needed to establish a gold standard, so that the discrepancy between an individual model and the reality can be obtained to determine the corresponding weight, but in-vivo measurement of the NGT insertion force is non-trivial and practically difficult as discussed above.

7. Conclusion

In this paper, a fuzzy-logic-based force model is proposed for NGT placement simulation. The force model is developed by directly leveraging the experience of clinicians in actual operations. The membership functions of the fuzzy system are defined by clustering, averaging and voting mechanism. The fuzzy rules are formulated based on the experience of clinicians and the fuzzy rule base is thus constructed. The membership functions and the fuzzy rules are adjusted interactively and iteratively until the feeling rendered by the force model was in agreement with the experience of the clinicians. A generalized force model is then created by averaging to integrate the force models of the individual clinicians. Integrating the friction force model, the fuzzy-logic-based method is used to generate the insertion force and drive the haptic device. This methodology is proposed to deal with the difficulty in quantifying the insertion force during real NGT placement. It can also be applied to the other similar situations, e.g. medical intubation or palpation, where in-vivo measurements are difficult for the modeling of the haptic feedback.

Based on the proposed force model, a prototype haptic simulation system for NGT placement is implemented. The system has been assessed by clinical teachers with extensive NGT placement experience. Their comments are positive and suggested that the simulator has good potential to be used in nursing curriculum to assist students in learning NGT placement. Further trials will be conducted with experienced clinicians and nursing students to evaluate the performance of the force model and the effectiveness of the haptic simulation system in NGT placement training.

Acknowledgments

This work was supported in part by the Research Grants Council of Hong Kong (PolyU 5134/12E), the Hong Kong Polytechnic University (G-UC93, G-YBKX), a scholarship donated by Nelson Y.C. Yu, and the Outstanding Youth Fund of the Jiangsu Province (BK20140001).

References

[1] N. A. Metheny, K. L. Meert, and R. E. Clouse, "Complications related to feeding tube placement," *Current opinion in gastroenterology,* vol. 23, pp. 178-182, 2007.

[2] O. Comas, Z. Taylor, J. Allard, S. Ourselin, S. Cotin, and J. Passenger, "Efficient nonlinear FEM for soft tissue modelling and its GPU implementation within the open source framework SOFA," in *Proc. International Symposium on Biomedical Simulation*, 2008, pp. 28-39.

[3] H. Courtecuisse, H. Jung, J. Allard, C. Duriez, D. Y. Lee, and S. Cotin, "GPU-based real-time soft tissue deformation with cutting and haptic feedback," *Progress in Biophysics and Molecular Biology,* vol. 103, pp. 159-168, 2010.

[4] K.-S. Choi, X. He, V. C.-L. Chiang, and Z. Deng, "A virtual reality based simulator for learning nasogastric tube placement," *Computers in Biology and Medicine,* vol. 57, pp. 103-115, 2015.

[5] L. Mudura, M. Bruer, I. H. Elhajj, G. Moore, and P. T. Ketcham, "A Virtual Nursing Simulator with Haptic Feedback for Nasotracheal Suctioning," in *Proc. Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*, 2006, pp. 698-703.

[6] D. K. Pai, K. Doel, D. L. James, J. Lang, J. E. Lloyd, J. L. Richmond, and S. H. Yau, "Scanning physical interaction behavior of 3D objects," in *Proc. Annual Conference on Computer Graphics and Interactive Techniques*, 2001, pp. 87-96.

[7] C. B. Zilles and J. K. Salisbury, "A constraint-based god-object method for haptic display," in *Proc. IEE/RSJ International Conference on Intelligent Robots and Systems, Human Robot Interaction, and Cooperative Robots*, 1995, pp. 146-151.

[8] D. C. Ruspini, K. Kolarov, and O. Khatib, "The haptic display of complex graphical environments," in *Proc. Annual Conference on Computer Graphics and Interactive Techniques*, 1997, pp. 345-352.

[9] J. E. Colgate, M. C. Stanley, and J. M. Brown, "Issues in the haptic display of tool use," in *Proc. IEE/RSJ International Conference on Intelligent Robots and Systems, Human Robot Interaction, and Cooperative Robots*, 1995, pp. 140-145.

[10] S. Hasegawa, M. Ishii, Y. Koike, and M. Sato, "Inter-process communication for force display of dynamic virtual world," in *Proc. ASME Dynamic Systems and Control Division.,* 1999, vol. 67, pp. 211-218.

[11] W. A. McNeely, K. D. Puterbaugh, and J. J. Troy, "Six degree-of-freedom haptic rendering using voxel sampling," in *Proc. Annual Conference on Computer Graphics and Interactive Techniques*, 1999, pp. 401-408.

[12] K. Moustakas, D. Tzovaras, and M. G. Strintzis, "SQ-Map: Efficient layered collision detection and haptic rendering," *IEEE Transactions on Visualization and Computer Graphics,* vol. 13, pp. 80-93, 2007.

[13] T. Alderliesten, P. A. Bosman, and W. J. Niessen, "Towards a real-time minimally-invasive vascular intervention simulation system," *IEEE Transactions on Medical Imaging,* vol. 26, pp. 128-132, 2007.

[14] L. Xu, Y. Tian, X. Jin, J. Chen, S. Schafer, K. Hoffmann, and J. Xu, "An improved endovascular guidewire position simulation algorithm," in *Proc. IEEE International Symposium on Biomedical Imaging,* 2012, pp. 1196-1199.

[15] J. Dequidt, M. Marchal, C. Duriez, E. Kerien, and S. Cotin, "Interactive simulation of embolization coils: Modeling and experimental validation," in *Proc. Medical Image Computing and Computer-Assisted Intervention, 2008*, pp. 695-702.
[16] V. Luboz, R. Blazewski, D. Gould, and F. Bello, "Real-time guidewire simulation in complex vascular models," *The Visual Computer,* vol. 25, pp. 827-834, 2009.
[17] D. K. Pai, "Strands: Interactive simulation of thin solids using cosserat models," in *Proc. Computer Graphics Forum*, 2002, pp. 347-352.
[18] M. Luo, H. Xie, L. Xie, P. Cai, and L. Gu, "A robust and real-time vascular intervention simulation based on Kirchhoff elastic rod," *Computerized Medical Imaging and Graphics,* vol. 38, pp. 735-743, 2014.
[19] D. Bi, J. Zhang, and G. Wang, "Fuzzy virtual coupling design for high performance haptic display," in *Proc. Fuzzy Systems and Knowledge Discovery,* pp. 481-481, 2005.
[20] M. Cheng, W. Marinovic, M. Watson, S. Ourselin, J. Passenger, H. De Visser, O. Salvado, and S. Riek, "Abdominal palpation haptic device for colonoscopy simulation using pneumatic control," *IEEE Transactions on Haptics,* vol. 5, pp. 97-108, 2012.
[21] N. Glossas and N. Aspragathos, "Fuzzy logic grasp control using tactile sensors," *Mechatronics,* vol. 11, pp. 899-920, 2001.
[22] O. Linda and M. Manic, "Fuzzy force-feedback augmentation for manual control of multirobot system," *IEEE Transactions on Industrial Electronics,* vol. 58, pp. 3213-3220, 2011.
[23] O. Linda and M. Manic, "Uncertainty-robust design of interval type-2 fuzzy logic controller for delta parallel robot," *IEEE Transactions on Industrial Informatics,* vol. 7, pp. 661-670, 2011.
[24] M. Chandrasekaran, M. Muralidhar, C. M. Krishna, and U. Dixit, "Application of soft computing techniques in machining performance prediction and optimization: a literature review," *The International Journal of Advanced Manufacturing Technology,* vol. 46, pp. 445-464, 2010.
[25] Q. Ren, L. Baron, K. Jemielniak, and M. Balazinski, "Modelling of dynamic micromilling cutting forces using Type-2 fuzzy rule-based system," in *Proc. IEEE International Conference on Fuzzy Systems*, 2010, pp. 1-7.
[26] I. Figueroa-Garcia, G. Sanchez-Sosa, R. Diaz-Dominguez, F. Rodriguez-Villagomez, J. C. Huegel, and A. Garcia-Gonzalez, "A nonparametric modeling approach of soft tissue deformation by ANFIS," in *Proc. IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, 2012, pp. 118-123.
[27] A. Radetzky and A. Nürnberger, "Visualization and simulation techniques for surgical simulators using actual patient's data," *Artificial Intelligence in Medicine,* vol. 26, pp. 255-279, 2002.
[28] A. Radetzky, A. Nürnberger, and D. P. Pretschner, "Elastodynamic Shape Modeler: A Tool for Defining the Deformation Behavior of Virtual Tissues1," *Radiographics,* vol. 20, pp. 865-881, 2000.
[29] W. Song, K. Yuan, and Y. Fu, "Haptic Modeling and Rendering Based on Neurofuzzy Rules for Surgical Cutting Simulation," *Acta Automatica Sinica,* vol. 32, pp. 193-199, 2006.
[30] S. Cotin, H. Delingette, and N. Ayache, "A hybrid elastic model for real-time cutting, deformations, and force feedback for surgery training and simulation," *The Visual Computer,* vol. 16, pp. 437-452, 2000.

[31] S. Kutuva, N. P. Reddy, Y. Xiao, X. Gao, S. Hariharan, and S. Kulkarni, "A novel and fast virtual surgical system using fuzzy logic," in *Proc. IADIS Multi Conference on Computer Graphics and Visualization*, 2006, pp. 277-281.
[32] S. Rajasekar, "Design of Hybrid Tissue Model in Virtual Tissue Cutting," in *Proc. International Conference on Research into Design*, 2009, pp. 466-471.
[33] A. J. O'Brien. "FLIHI: Fuzzy Logic Implemented Hill-based Muscle Model." D. Sc. thesis, The George Washington University, 2006.
[34] F. Nowshiravan Rahatabad, A. H. Jafari, A. Fallah, and J. Razjouyan, "A fuzzy-genetic model for estimating forces from electromyographical activity of antagonistic muscles due to planar lower arm movements: The effect of nonlinear muscle properties," *Biosystems,* vol. 107, pp. 56-63, 2012.
[35] E. H. Mamdani and S. Assilian, "An experiment in linguistic synthesis with a fuzzy logic controller," in *Proc. International Journal of Man-machine Studies,* vol. 7, pp. 1-13, 1975.
[36] G. A. Korn, *Neural networks and fuzzy-logic control on personal computers and workstations*: MIT Press, 1995.
[37] T. J. Ross, *Fuzzy logic with engineering applications*: Wiley, 2009.
[38] R. Kruse, J. E. Gebhardt, and F. Klowon, *Foundations of fuzzy systems*: John Wiley & Sons, Inc., 1994.
[39] J. C. Bezdek, R. Ehrlich, and W. Full, "FCM: The fuzzy c-means clustering algorithm," *Computers & Geosciences,* vol. 10, pp. 191-203, 1984.
[40] T. Bilgiç and I. B. Türkşen, "Measurement of membership functions: theoretical and empirical work," in *Fundamentals of fuzzy sets*, ed: Springer, 2000, pp. 195-227.
[41] H. Takagi and I. Hayashi, "NN-driven fuzzy reasoning," *International Journal of Approximate Reasoning,* vol. 5, pp. 191-212, 1991.
[42] C.-C. Yang and N. Bose, "Generating fuzzy membership function with self-organizing feature map," *Pattern Recognition Letters,* vol. 27, pp. 356-365, 2006.
[43] R. Mahajan, R. Gupta, and A. Sharma, "Role of neck flexion in facilitating nasogastric tube insertion," *Anesthesiology,* vol. 103, pp. 446-447, 2005.
[44] M. Harvey and G. Cave, "A novel method to assist gastric tube insertion: a case series," *Emergency Medicine Journal,* vol. 27, pp. 613-615, 2010.
[45] M. J. Ackerman, "The visible human project," *Proceedings of the IEEE,* vol. 86, pp. 504-511, 1998.
[46] R. J. Hathaway and J. C. Bezdek, "Recent convergence results for the fuzzy c-means clustering algorithms," *Journal of Classification,* vol. 5, pp. 237-247, 1988.
[47] J.-S. Jang and C.-T. Sun, "Neuro-fuzzy modeling and control," in *Proc. IEEE special issue on Engineering Applications of Fuzzy Logic*, 1995, pp. 378-406.
[48] L. Reznik, *Fuzzy controllers handbook: how to design them, how they work*: Newnes, 1997.
[49] P.-A. Heng, T.-T. Wong, K.-M. Leung, Y.-P. Chui, and H. Sun, "A haptic needle manipulation simulator for chinese acupuncture learning and training," *International Journal of Image and Graphics,* vol. 6, pp. 205-230, 2006.
[50] S. Ullrich and T. Kuhlen, "Haptic palpation for medical simulation in virtual environments," *IEEE Transactions on Visualization and Computer Graphics,* vol. 18, pp. 617-625, 2012.

Appendix

Table A1. Fuzzy rules in the questionnaire.

No.	Rule	Very Small	Small	Medium	Large	Very Large
1	IF Tube Lubrication IS Poor AND Tube Tip Position IS in Nasal Cavity, THEN Force Change IS:	☐	☐	☐	☐	☐
2	IF Tube Lubrication IS Poor AND Tube Tip Position IS in Nasopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
3	IF Tube Lubrication IS Poor AND Tube Tip Position IS in Oropharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
4	IF Tube Lubrication IS Poor AND Tube Tip Position IS in Laryngopharynx THEN Force Change IS:	☐	☐	☐	☐	☐
5	IF Tube Lubrication IS Poor AND Tube Tip Position IS in Oesophagus, THEN Force Change IS:	☐	☐	☐	☐	☐
6	IF Tube Lubrication IS Medium AND Tube Tip Position IS in Nasal Cavity, THEN Force Change IS:	☐	☐	☐	☐	☐
7	IF Tube Lubrication IS Medium AND Tube Tip Position IS in Nasopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
8	IF Tube Lubrication IS Medium AND Tube Tip Position IS in Oropharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
9	IF Tube Lubrication IS Medium AND Tube Tip Position IS in Laryngopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
10	IF Tube Lubrication IS Medium AND Tube Tip Position IS in Oesophagus, THEN Force Change IS:	☐	☐	☐	☐	☐
11	IF Tube Lubrication IS Well AND Tube Tip Position IS in Nasal Cavity, THEN Force Change IS:	☐	☐	☐	☐	☐
12	IF Tube Lubrication IS Well AND Tube Tip Position IS in Nasopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
13	IF Tube Lubrication IS Well AND Tube Tip Position IS in Oropharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
14	IF Tube Lubrication IS Well AND Tube Tip Position IS in Laryngopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
15	IF Tube Lubrication IS Well AND Tube Tip Position IS in Oesophagus, THEN Force Change IS:	☐	☐	☐	☐	☐
16	IF Neck Flexion IS Small AND Tube Tip Position IS in Nasal Cavity, THEN Force Change IS:	☐	☐	☐	☐	☐
17	IF Neck Flexion IS Small AND Tube Tip Position IS in Nasopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
18	IF Neck Flexion IS Small AND Tube Tip Position IS in Oropharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
19	IF Neck Flexion IS Small AND Tube Tip Position IS in Laryngopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
20	IF Neck Flexion IS Small AND Tube Tip Position IS in Oesophagus, THEN Force Change IS:	☐	☐	☐	☐	☐
21	IF Neck Flexion IS Medium AND Tube Tip Position IS in Nasal Cavity, THEN Force Change IS:	☐	☐	☐	☐	☐
22	IF Neck Flexion IS Medium AND Tube Tip Position IS in Nasopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
23	IF Neck Flexion IS Medium AND Tube Tip Position IS in Oropharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
24	IF Neck Flexion IS Medium AND Tube Tip Position IS in Laryngopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
25	IF Neck Flexion IS Medium AND Tube Tip Position IS in Oesophagus, THEN Force Change IS:	☐	☐	☐	☐	☐
26	IF Neck Flexion IS Large AND Tube Tip Position IS in Nasal Cavity, THEN Force Change IS:	☐	☐	☐	☐	☐
27	IF Neck Flexion IS Large AND Tube Tip Position IS in Nasopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
28	IF Neck Flexion IS Large AND Tube Tip Position IS in Oropharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
29	IF Neck Flexion IS Large AND Tube Tip Position IS in Laryngopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
30	IF Neck Flexion IS Large AND Tube Tip Position IS in	☐	☐	☐	☐	☐

	Oesophagus, THEN Force Change IS:					
31	IF Speed IS Slow AND Tube Tip Position IS in Nasal Cavity, THEN Force Change IS:	☐	☐	☐	☐	☐
32	IF Speed IS Slow AND Tube Tip Position IS in Nasopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
33	IF Speed IS Slow AND Tube Tip Position IS in Oropharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
34	IF Speed IS Slow AND Tube Tip Position IS in Laryngopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
35	IF Speed IS Slow AND Tube Tip Position IS in Oesophagus, THEN Force Change IS:	☐	☐	☐	☐	☐
36	IF Speed IS Medium AND Tube Tip Position IS in Nasal Cavity, THEN Force Change IS:	☐	☐	☐	☐	☐
37	IF Speed IS Medium AND Tube Tip Position IS in Nasopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
38	IF Speed IS Medium AND Tube Tip Position IS in Oropharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
39	IF Speed IS Medium AND Tube Tip Position IS in Laryngopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
40	IF Speed IS Medium AND Tube Tip Position IS in Oesophagus, THEN Force Change IS:	☐	☐	☐	☐	☐
41	IF Speed IS Fast AND Tube Tip Position IS in Nasal Cavity, THEN Force Change IS:	☐	☐	☐	☐	☐
42	IF Speed IS Fast AND Tube Tip Position IS in Nasopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
43	IF Speed IS Fast AND Tube Tip Position IS in Oropharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
44	IF Speed IS Fast AND Tube Tip Position IS in Laryngopharynx, THEN Force Change IS:	☐	☐	☐	☐	☐
45	IF Speed IS Fast AND Tube Tip Position IS in Oesophagus, THEN Force Change IS:	☐	☐	☐	☐	☐

Table A2 Fuzzy rules in the fuzzy rule base of subject *S*4.

No.	Fuzzy Rules
1.	IF Tube Lubrication IS Well AND Tube Tip Position IS in Nasal Cavity THEN Force IS Very Small
2.	IF Tube Lubrication IS Well AND Tube Tip Position IS in Nasopharynx THEN Force IS Small
3.	IF Tube Lubrication IS Well AND Tube Tip Position IS in Laryngopharynx THEN Force IS Small
4.	IF Tube Lubrication IS Well AND Tube Tip Position IS in Esophagus THEN Force IS Medium
5.	IF Tube Lubrication IS Well AND Tube Tip Position IS in Stomach THEN Force IS Very Small
6.	IF Tube Lubrication IS Medium AND Tube Tip Position IS in Nasal Cavity THEN Force IS Very Small
7.	IF Tube Lubrication IS Medium AND Tube Tip Position IS in Nasopharynx THEN Force IS Small
8.	IF Tube Lubrication IS Medium AND Tube Tip Position IS in Laryngopharynx THEN Force IS Small
9.	IF Tube Lubrication IS Medium AND Tube Tip Position IS in Esophagus THEN Force IS Large
10.	IF Tube Lubrication IS Medium AND Tube Tip Position IS in Stomach THEN Force IS Small
11.	IF Tube Lubrication IS Poor AND Tube Tip Position IS in Nasal Cavity THEN Force IS Large
12.	IF Tube Lubrication IS Poor AND Tube Tip Position IS in Nasopharynx THEN Force IS Very Large
13.	IF Tube Lubrication IS Poor AND Tube Tip Position IS in Laryngopharynx THEN Force IS Very Large
14.	IF Tube Lubrication IS Poor AND Tube Tip Position IS in Esophagus THEN Force IS Very Large
15.	IF Tube Lubrication IS Poor AND Tube Tip Position IS in Stomach THEN Force IS Large
16.	IF Neck Flexion IS Small AND Tube Tip Position IS in Nasal Cavity THEN Force IS Very Small
17.	IF Neck Flexion IS Small AND Tube Tip Position IS in Nasopharynx THEN Force IS Medium
18.	IF Neck Flexion IS Small AND Tube Tip Position IS in Laryngopharynx THEN Force IS Medium
19.	IF Neck Flexion IS Small AND Tube Tip Position IS in Esophagus THEN Force IS Medium
20.	IF Neck Flexion IS Small AND Tube Tip Position IS in Stomach THEN Force IS Small
21.	IF Neck Flexion IS Medium AND Tube Tip Position IS in Nasal Cavity THEN Force IS Very Small
22.	IF Neck Flexion IS Medium AND Tube Tip Position IS in Nasopharynx THEN Force IS Medium
23.	IF Neck Flexion IS Medium AND Tube Tip Position IS in Laryngopharynx THEN Force IS Medium
24.	IF Neck Flexion IS Medium AND Tube Tip Position IS in Esophagus THEN Force IS Medium
25.	IF Neck Flexion IS Medium AND Tube Tip Position IS in Stomach THEN Force IS Small
26.	IF Neck Flexion IS Large AND Tube Tip Position IS in Nasal Cavity THEN Force IS Very Small
27.	IF Neck Flexion IS Large AND Tube Tip Position IS in Nasopharynx THEN Force IS Medium
28.	IF Neck Flexion IS Large AND Tube Tip Position IS in Laryngopharynx THEN Force IS Large
29.	IF Neck Flexion IS Large AND Tube Tip Position IS in Esophagus THEN Force IS Very Large
30.	IF Neck Flexion IS Large AND Tube Tip Position IS in Stomach THEN Force IS Medium
31.	IF Speed IS Slow AND Tube Tip Position IS in Nasal Cavity THEN Force IS Very Small
32.	IF Speed IS Slow AND Tube Tip Position IS in Nasopharynx THEN Force IS Medium
33.	IF Speed IS Slow AND Tube Tip Position IS in Laryngopharynx THEN Force IS Medium
34.	IF Speed IS Slow AND Tube Tip Position IS in Esophagus THEN Force IS Small
35.	IF Speed IS Slow AND Tube Tip Position IS in Stomach THEN Force IS Very Small
36.	IF Speed IS Medium AND Tube Tip Position IS in Nasal Cavity THEN Force IS Small
37.	IF Speed IS Medium AND Tube Tip Position IS in Nasopharynx THEN Force IS Large
38.	IF Speed IS Medium AND Tube Tip Position IS in Laryngopharynx THEN Force IS Large
39.	IF Speed IS Medium AND Tube Tip Position IS in Esophagus THEN Force IS Large
40.	IF Speed IS Medium AND Tube Tip Position IS in Stomach THEN Force IS Small
41.	IF Speed IS Fast AND Tube Tip Position IS in Nasal Cavity THEN Force IS Medium
42.	IF Speed IS Fast AND Tube Tip Position IS in Nasopharynx THEN Force IS Very Large
43.	IF Speed IS Fast AND Tube Tip Position IS in Laryngopharynx THEN Force IS Very Large
44.	IF Speed IS Fast AND Tube Tip Position IS in Esophagus THEN Force IS Very Large
45.	IF Speed IS Fast AND Tube Tip Position IS in Stomach THEN Force IS Large

Kup-Sze Choi (M’97) received his Ph.D. degree in computer science and engineering from the Chinese University of Hong Kong. He is currently an associate professor in the School of Nursing, The Hong Kong Polytechnic University, and the Director of the Centre for Smart Health and the PolyU-Henry G. Leong Mobile Integrative Health Centre. His research interest covers innovative and technological applications in healthcare, with focus on virtual reality and computational intelligence.

Xue-Jian HE received his Ph.D. degree in mechanical engineering from the University of Hong Kong. He is currently a research associate in the School of Nursing, the Hong Kong Polytechnic University. His research interests include haptic modeling, human-computer interaction, medical simulation, virtual reality in medicine and health care.

Zhaohong Deng (M'2012, SM'2014) received the B.S. degree in physics from Fuyang Normal College, Fuyang, China, in 2002, and the Ph.D. degree in light industry information technology and engineering from Jiangnan University, Wuxi, China, in 2008. He is currently a professor in the School of Digital Media, Jiangnan University. His current research interests include computational intelligence and pattern recognition. He serves as the associate editor of four international journals including Neurocomputing, PLOS one. He has published about 80 papers in international/national journals.

Vico Chiang is a registered nurse (HK & Australia) and an assistant professor in the School of Nursing, The Hong Kong Polytechnic University. His research interests are in family care in the lifespan (including disasters care) and nursing education.

Harry J. Qin received his Ph.D. (Computer Science and Engineering) from the Chinese University of Hong Kong in 2009. He is currently an assistant professor in the School of Nursing of the Hong Kong Polytechnic University, and a key member in the Centre for Smart Health. His research interests include virtual/augmented environments for healthcare training, computer-aided rehabilitation, health informatics, medical image processing and tele-healthcare.