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Haptic interaction in VR-based paracentesis simulation for dexterity enhancement and assessment

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Abstract. In this paper, we describe the development of an interactive virtual reality (VR) system that aims to realistically simulate specific paracentesis clinical procedures (particularly the procedure involved in the catheterization of the subclavian vein). A simplified elasto-static finite-element model is used for the physically based simulation of the deformable tissues, particularly skin deflection during needle insertion. The VR-based simulation is being coupled with a haptic feedback device to provide to the user realistic feeling of the interaction forces applied during the simulated paracentesis procedure. The system described is developed in the frames of a research project aiming to develop a larger-scale virtual environment simulator of emergency room (ER) scenarios and protocols for clinical skill training and assessment.

Keywords: Haptics; Virtual reality; Tissue deformation modeling; Paracentesis simulation; Clinical skill training

1. Introduction

The barrier between theoretical knowledge and clinical performance is probably the biggest problem as far as education of medical doctors and nursing professionals is concerned. Efficient clinical training of healthcare professionals constitutes undoubtedly a very difficult task, which is nowadays primarily based on the close supervision and monitoring by a specialist trainer, on the patient's consent, but also on suitable general conditions; a combination of factors which is not always attainable since the main and primary concern always remains, that of treating the patient in the best possible way. Based on the above remarks, we can say that the difficulties associated with clinical training in specific medical practice hospital environments (such as, the Emergency Rooms or the Intensive Care Units, where the ultimate degree of dexterity together with "real-time" clinical skills are needed) are more than evident. The timely and persistent

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adaptation of the trainee medical doctor from the theoretical education field to the clinical "hands-on" practice on the hospital environment, constitutes undoubtedly a real challenge and a primary educational objective in the Health Sciences. Training on cadavers, which is still used today for over a century now, is not always adequate to cover other than special needs, not always of primary importance in surgical education and training. The use of animals constituted an "attractive" solution for decades, but for obvious reasons, related to human ethics as well as evolving legislation issues, as well as due to the need for important investments in terms of the related infrastructure, this solution has been practically abandoned. The experience obtained from the application of flight-simulation systems for the training of pilots, in an application environment that resembles in a way the field of clinical practice (in terms of the need for rapid complex data evaluation and critical decision-making), has more recently increased interest towards the use of virtual reality (VR) technologies in the medical education field.

In this paper, we describe on-going work carried out in the frames of a research project aiming to develop a computer-assisted educational platform based on a dynamic simulation system of an emergency room (ER) hospital environment. A set of clinical protocols and real case scenarios is implemented within the ER simulator, also incorporating VR techniques for visualization and user interaction. The system will enable the user to examine (virtual clinical data examination), evaluate (vital signs, clinical findings and medical images, obtained from a database of pre-stored clinical cases) and treat the virtual patient (by commanding the execution of certain clinical procedures). The system is designed to support both asynchronous self-education and training in specific clinical protocols, as well as real-time collective training through the dynamic simulation of realistic clinical scenarios, involving active collaboration of two or more actors (including medical/nursing trainees and trainers) under time pressure.

In this context, we are developing an interactive virtual reality system that aims to realistically simulate paracentesis operations, and more particularly the procedure involved in the catheterisation of the subclavian vein. This is one of the most common procedures in clinical practice and is often involved in the treatment of patients in an ER situation. This operation is particularly difficult to learn, and requires a combination of visual and haptic skills in order to identify the needle insertion point, and to control the needle position and orientation during penetration. To develop a realistic and accurate physically based dynamic simulation, a simplified finite-element model is used for the deformable tissues and anatomical structures of the human body involved in this procedure. Moreover, to incorporate the sense of touch and improve the impact of the training system in terms of "teaching basic clinical skills", a haptic interaction system is currently under development, coupling the VR-based simulation with a haptic device. The challenges addressed at this stage are twofold: (i) from a technical point of view, to achieve a trade-off between realism (that is, accuracy of the physically based dynamic simulation) and real-time performance (necessary particularly for a stable and "transparent" haptic interaction with the system), imposing model simplifications, based on specific assumptions and approximations, in order to achieve fast computations for the feedback forces distribution; (ii) from an educational/training point of view, to conduct human factors evaluation studies in order to identify the critical factors affecting the performance of the system in terms of clinical skill training and assessment.

2. Tissue deformation modelling for paracentesis simulation

The first step in achieving a realistic and accurate physically based paracentesis simulation is to develop models for the deformable tissues and anatomical structures of the human body involved in this clinical procedure. Elastic deformation modelling of soft tissues is a wide research area in the field of 3D computer graphics and animation, with many applications particularly in VR-based systems. The two most widely employed generic methodologies are based on: (a) mass-spring models, where the deformable object is modelled as a lattice of point masses interconnected by spring/damping elements; and (b) finite-element (FE) models, which are based on the discretisation of a continuum elasticity model [1].

Particularly, modelling the deformation of human tissues and organs for surgery simulation has turned out to be a real challenge, due to the lack of accurate knowledge about their physical properties, and the very few existing experimental data provided by in vivo studies. The need is for both realism and speed, but for surgical simulation systems, the emphasis is definitely put on real-time interaction. This has turned scientific interest towards the development of accurate mathematical models, but which can be at the same time treated using efficient numerical computation algorithms. Examples of such methodologies for modelling human soft tissue by applying FE techniques in a computationally efficient framework are presented in [2] and [3]. More recently, the use of FE models to develop a needle insertion simulation system is proposed in Ref. [4].

The use of FE models is typically preferred for interactive surgical simulation applications, mainly because these models are parameterised and tuned more intuitively than mass-spring nets. However, to enable real-time interaction with 3D FE models, long pre-processing steps are required, imposing additional constraints related to shape changes and deformation limits. The use of "intelligent model simplifications" for particular applications may overcome these problems in a task-specific context. In this framework, we propose the use of a simple 1D finite-element model to simulate deformation of the skin, based on an assumption of radial symmetry properties in specific configurations of needle insertion operations. Our goal is to achieve a realistic interaction, both visual (based on deformation rendering) and haptic (based on real-time reflected force computation), in real-time and with a "reasonable" accuracy. This means that visual and haptic results should match as closely as possible available real experimental data provided by in vivo studies reported in the literature.

The elastostatic model used in this work to simulate skin deformation in paracentesis operations consists of a simplified 1D "chord-like" medium, exhibiting both anisotropic behaviour in deformation magnitude, and inhomogeneity properties in length. The media is discretised using the FE method [5], and is considered to be sub-divided into separate homogeneous regions. The model is parameterised according to an assumed linear stiffness increase away from the centre, considered as the contact (needle insertion) point, also assuming linearly increasing region width. Besides these inhomogeneous characteristics, we assume anisotropy behaviour in deformation magnitude, with stiffness coefficients increasing according to a typical exponential formula.

Simulation results are illustrated in Fig. 1 (number of elements = 150), where vertical deformation is plotted against distance from the contact point. The obtained results are compared with the experimental data reported in Refs. [6,7], providing in vivo measure-

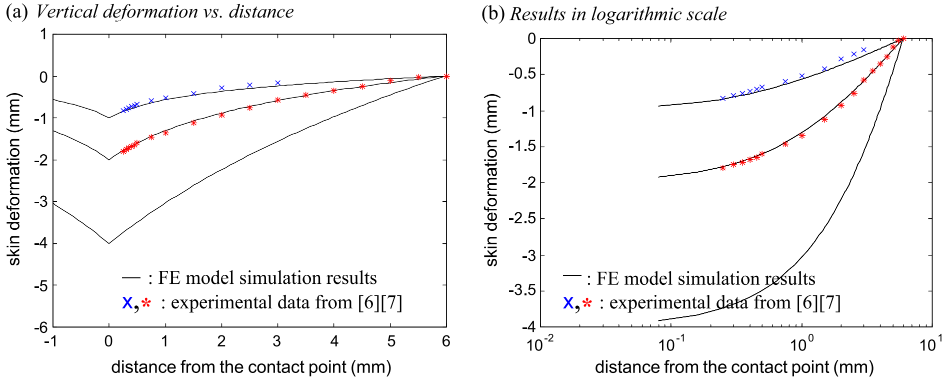

Fig. 1. Skin deformation predicted by the 1D FE model, compared with the experimental data from Refs. [6,7].

ments of skin surface deflection profiles under line loads. We can see that the simplified 1D finite-element model, with anisotropy and inhomogeneity properties described above, accurately predicts the real skin deformation profiles, and can be thus used to provide a realistic and computationally efficient simulation in the specific paracentesis application context considered in this paper.

3. Virtual reality system: visual and haptic display

3.1. 3D graphics models and rendering

The FE-based skin-deformation simulation method described in the previous section is integrated within the VR-based paracentesis simulator that is currently under development. The 3D (surface) models of the human body (outer skin), as well as those for the different anatomical structures (inner organs) involved in such clinical operations (venal tree, muscle groups, lungs and bony structures), are extracted from 3D anatomical models commercially available (http://www.cacheforce.com/), and linked to the main application program, which is implemented using C++ and OpenGL for 3D rendering.

Fig. 2 shows two screen snapshots of the VR-based paracentesis simulation, including 3D visualization of deformed skin (in solid and alpha-transparency mode) and venal tree, during simulated needle insertion. In the current simulator configuration, the system continuously monitors and registers the trajectory of the needle, and its intersection with the surface of the skin and the subclavian vein. The goal is twofold: (a) to provide realistic visual (skin deformation) and haptic (computation of reflected force) feedback, and (b) to enable the development of computer-automated skill assessment modules for different clinical training scenarios. For each training scenario, a number of appropriate scores will be computed based on a set of established performance indices. For instance, we can measure on-line a set of dynamic parameters, such as the amount of tissue deformation (related to human tissue damage), when performing the simulated paracentesis operation, as well as the "optimality" of the path followed by the needle during skin puncturing and insertion into a deep vessel, to establish average or special-purpose performance scores and advice the user on ameliorating his/her technique.

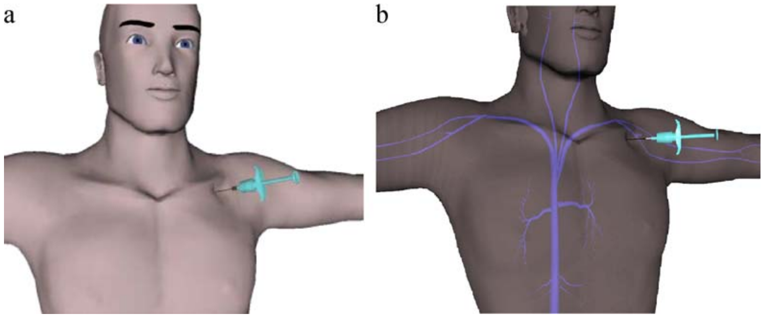

Fig. 2. VR-based paracentesis simulation: 3D visualization in solid and alpha-transparency mode.

Our final goal is to integrate this interactive simulator within a larger-scale computer-assisted clinical education and training platform, based on the dynamic simulation of complete clinical scenarios and medical protocols. The initial focus of the platform (within the frames of a national research project, called VRES) is targeted onto a set of medical/nursing procedures within a simulated emergency room (ER) environment. Initial scenarios are being developed around a complete set of cardio-pulmonary resuscitation (CPR) protocols in ER/trauma cases. From a technical point of view, the key issues here concern: (i) modelling and real-time computer-based simulation of selected clinical scenarios, built upon a multi-parameter decision-tree model, (ii) definition and implementation of training scenarios, with the emphasis being on real-time dynamic simulation and user interaction with the system, (iii) definition and implementation of the appropriate user interaction metaphors, including VR navigation, and multimodal (visual/haptic) feedback.

3.2. Haptics

Learning to safely and accurately perform a specific paracentesis operation is a particularly difficult task, requiring a combination of visual and tactile skills to identify the needle insertion point, and control the needle position and orientation during penetration. To provide realistic feedback to the medical/nursing trainee or novice user and improve the impact of the training system in terms of “teaching basic clinical skills”, the system should not be limited in providing only 3D visualizations of the simulated medical procedures, but must also enable real-time haptic interaction, incorporating the sense of touch in the dynamic simulation. For this reason, the VR-based simulation will be coupled with a haptic device (a Phantom™ desktop force feedback device), in a novel dual hand configuration, to provide to the user realistic feeling of the interaction forces.

The haptic interaction system should involve both hands of the user, working in coordination to perform the simulated clinical procedure. For instance, when inserting a needle during paracentesis of the subclavian vein, the left hand palpates the subclavian anatomic area to find and recognize the anatomic landmark used as guide point, while the right hand inserts and orientates the needle through the selected point on the skin. Such dual-hand coordinated actions should be supported by the final platform. This is a challenging objective, both from technical and “human-factors” perspective, and constitutes on its own an innovative aspect of the system that is currently under development, particularly concerning integration of such a "haptic interaction" mode into a complete clinical dexterity enhancement and skill assessment platform.

4. Conclusion and future work

This paper described the development of an interactive virtual reality (VR) system aiming to realistically simulate specific paracentesis clinical procedures (particularly catheterization of the subclavian vein). A simple 1D finite-element model, with anisotropy and inhomogeneity properties, is used for the physically based simulation of tissue deformation. The proposed model, simulating skin deflection during needle insertion, is experimentally validated compared to real skin deformation data available in the literature. In the future, a more complex layered structure will be considered, involving 3D anatomical models not only of the skin but also of underlying structures (subcutaneous fat layer, major muscle groups, lungs, and bones).

The principal objective of this research is to enable medical/nursing students and trainees to acquire basic clinical skills through unlimited practicing in VR, before even touching a real patient, and thus without invoking any pain, discomfort or risk for real patients. However, our goal is to develop a system that will also provide self-evaluation and skill-assessment functionalities, as well as automatic correction and computer-assisted guidance features, through the detailed analysis of the technical mistakes performed by the trainee. It is thus foreseen that the same real-time haptic interaction platform will not only be used as a tool for dexterity enhancement, but also to monitor the performance of the trainee, introducing objective quantifiable measures and standardized criteria for the evaluation of clinical adequacy, technical dexterity, and psychokinetic skills. Our final goal is to integrate this interactive simulator within a larger-scale computer-assisted clinical education/training platform, based on the interactive simulation of complete scenarios and protocols related to the operation in an emergency room environment, for clinical skill training and assessment.

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