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Download date: 02 May 2019
Chapter 8

Augmented reality-based navigation system for wrist arthroscopy: feasibility

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Published JWS 2013; 02(04): 294-298
ABSTRACT

Purpose
In video surgery, and more specifically in arthroscopy, one of the major problems is positioning the camera and instruments within the anatomic environment. The concept of computer-guided video surgery has already been used in ear, nose, and throat (ENT), gynecology, and even in hip arthroscopy. These systems, however, rely on optical or mechanical sensors, which turn out to be restricting and cumbersome. The aim of our study was to develop and evaluate the accuracy of a navigation system based on electromagnetic sensors in video surgery.

Methods
We used an electromagnetic localization device (Aurora, Northern Digital Inc., Ontario, Canada) to track the movements in space of both the camera and the instruments. We have developed a dedicated application in the Python language, using the VTK library for the graphic display and the Open CV library for camera calibration.

Results
A prototype has been designed and evaluated for wrist arthroscopy. It allows display of the theoretical position of instruments onto the arthroscopic view with useful accuracy.

Discussion
The augmented reality view represents valuable assistance when surgeons want to position the arthroscope or locate their instruments. It makes the maneuver more intuitive, increases comfort, saves time, and enhances concentration.
INTRODUCTION

One of the main problems in endoscopic surgery is positioning and displacing both the optic device and the surgical instruments within the operative field. Triangulation is only mastered after years of training. In order to smooth the learning curve, solutions have been developed in some disciplines thanks to computer-assisted surgery, such as in laparoscopy (1), arthroscopy of the temporomandibular joint (2) or hip arthroscopy (3).

These computer-assisted endoscopic surgery systems require merging two kinds of data, anatomic and instrumental, so that surgeons can better find their bearings in a limited surgical field (4). Anatomical data corresponds to a three-dimensional reconstruction of the surgical field of the patient from CT or MRI acquisitions. Instrumental data corresponds to a three-dimensional representation of surgical instruments from acquisitions thanks to sensors.

In wrist arthroscopy, mastering the positioning and displacement of optical device and surgical instruments in the joints requires a long learning curve (5, 6). To our knowledge, no computer-assisted system for arthroscopic surgery of the wrist facilitating the localization of optical device and instruments has yet been developed to smooth the learning curve.

The aim of this study was to develop and evaluate the feasibility of a computer-assisted system for arthroscopic surgery of the wrist through augmented reality and using electromagnetic sensors.

MATERIAL AND METHODS

The material was composed of a fresh cadaver, an arthroscopy column and an augmented reality navigation system for wrist arthroscopy that has been developed for this study.

The left forearm of the cadaver has been sectioned at the level of the proximal quarter. It has been installed in 80 N vertical traction on a traction tower (Fig. 1).

The augmented reality navigation system for wrist arthroscopy was composed of three devices: an arthroscopic image collection device, an electromagnetic localization device, and a data processing device.
The arthroscopic image collection device was composed of an arthroscope (Fig. 1) fitted with a 2.4 mm optic with 30° oblique vision and a high resolution camera (H3-Z® HD camera head, Storz™, Tuttlingen, Germany), and a video column for arthroscopy (Image 1© Hub, Storz™, Tuttlingen, Germany).

The objective of the electromagnetic localization system (Aurora®, Northern Digital Inc™, Ontario, Canada) was to track the movements in space of the arthroscope and a little ferromagnetic palpator for arthroscopy designed to reduce electromagnetic interferences. This device had on the one hand an electromagnetic field transmitter (Planar Field Generator) and on the other hand solenoid-shaped electromagnetic sensors with 6 degrees of freedom (DOF) connected to Sensor Interface Units. The electromagnetic field transmitter and sensor interface units were linked to a System Control Unit. Two electromagnetic sensors had been attached to the palpator and an electromagnetic sensor had been attached to the arthroscope (Fig. 1). A system control unit gave sensor position and orientation in real-time, with accuracy within the mm and degree range (7). This data was transmitted to the data processing device via a serial port.

The data processing device was composed of a laptop and an application designed to generate augmented reality images. This application has been implemented in Python language (8), and used the open source library Visualisation Toolkit (VTK) (9) for the graphic display, and the open source library OpenCV (10) for the processing of video
images. The application captured the spatial position of electromagnetic sensors in real-time from the data flow originating from the electromagnetic localization device.

The method consisted in calibrating the palpator, the arthroscope, the endoscopic camera and the wrist.

Palpator calibration (Fig. 2) has been done following the pivot method (11). A dedicated function took the successive positions of the palpator’s electromagnetic sensors into account during a circumduction movement around the palpator tip. From all sensor positions, this function computed an estimation of the theoretical position of the palpator tip. At the end of calibration, the function turned around the transformation matrix expressing the relative position of the palpator tip with respect to the position of electromagnetic sensors.

Arthroscope calibration has been done through palpation of three reference points with the palpator tip. A dedicated function took the position of the arthroscope tip, of the camera-optic junction and of the cold light connection into account. At the end of calibration, the function turned around the transformation matrix expressing the relative position of arthroscope tip with respect to the position of the electromagnetic sensor.
Figure 3: Endoscopic camera calibration according to the method described by Tsai. A checkered pattern with known dimensions was localized in space through palpation with the probe, then recorded for a few seconds with the arthroscope, while the electromagnetic localization device collected the positions of the arthroscope-associated sensor. The navigation system then determined intrinsic and extrinsic parameters of the optic-camera set.

Figure 4: After probe and arthroscope calibration, the navigation system displayed a virtual reality model of the probe and the arthroscope.
Calibration of the endoscopic camera (Fig. 4) has been done following the method described by Tsai (12), camera rotation around the axis of the optic having been blocked so as to simplify the registration problem of optics with oblique vision. The aim was to determine on the one hand intrinsic parameters of the optic-camera set corresponding to the internal geometry of the camera and to the characteristics of the camera, and on the other hand extrinsic parameters corresponding to position and orientation of the optic-camera set within the adopted spatial reference frame. This has been realized thanks to specific functions of the OpenCV library. In practice, a checkered pattern with known dimensions was localized in space through palpation with the palpator, and then filmed for a few seconds by the arthroscope while the electromagnetic localization device was collecting the positions of the sensor associated to the arthroscope. A collection of couples (arthroscopic image of the checkered pattern, actual sensor position) was sent in input to a function which, after segmentation of the checkered pattern, turned around intrinsic and extrinsic parameters of the optic-camera set.

Calibration ended with the localization of three reference points on the back of the cadaver hand which was fixed to the traction tower: heads of the second and fifth metacarpal bones and Lister’s tubercule.

Figure 5a-c: Navigation system for wrist arthroscopy: (a) Real view of the surgical field. (b) Virtual reality: scene representing the surgical field, where the arthroscope, probe, and wrist have been modelled. (c) Augmented reality: superimposition of the arthroscope shape onto the arthroscopic image, modeled in virtual reality
RESULTS

From initial calibration data (registration matrix of the palpator and the arthroscope, intrinsic and extrinsic parameters of the optic-camera set, and wrist position) and data collected in real-time by the electromagnetic localization device (sensor position associated to the palpator and the arthroscope), the data processing device modeled virtual reality which featured a model of the palpator, the arthroscope and the wrist (Fig. 3 to 5).

The data processing device simulated arthroscopic images by positioning and orientating the point of view within the virtual reality according to arthroscope position and intrinsic and extrinsic parameters of the optic-camera set.

Through the superimposition of these virtual arthroscopic images onto real arthroscopic images, the data processing device generated augmented reality images (Fig. 5).

DISCUSSION

The purpose of surgical navigation systems (computer-guided systems) is to display information through which surgeons can better find their bearings within the space of the operating field and within the anatomical space of the patient. This information comes from data that can be acquired before or during the intervention according to various sources: 3D reconstruction of tomographic data, fluoroscopic images, palpation of anatomical landmarks or kinematic data. In order to facilitate the surgeon's reading during an intervention, this information is presented visually in most cases according to two main modes: augmented virtuality and augmented reality.

Augmented virtuality consists in representing a virtual environment on the basis of real data. Typically, we are talking about computer-assisted systems for hip or knee arthroplasty, where the positioning of the prosthesis is figured on an anatomical model.

Augmented reality consists in representing virtual data on a real image. Since Thomas Caudell invented this concept in the early 1990s (13), augmented reality has been applied to many domains (14). In medicine, it naturally found applications in techniques using an optical device and/or a camera: coelioscopy (4), arthroscopy (15), endoscopy (16, 17) and microsurgery (18). In all the fields it has been used, the purpose of augmented reality was to simplify and accelerate access to complex data by associating them to elements of the field of vision of surgeons.
Either they use augmented virtuality or augmented reality, most surgical navigation systems rely on optical or mechanical sensors which turn out to be restricting and cumbersome.

Optoelectronic localization devices are the most frequently used in computer-assisted surgery (3). They present however a greatly limiting feature that makes them inappropriate for computer-navigated arthroscopy: sensors cannot be localized once they have left the field of vision of the stereo camera (4). And it just so happens that the operative field in wrist arthroscopy is necessarily cluttered with visual obstacles such as the patient’s limb, the traction column, the surgeon’s hands, instruments, etc.

Mechatronic localization systems are less frequently used. They help getting around the issues linked to sensor occultation. For hip arthroscopy, a mechatronic localization device has been developed and evaluated (3, 19). Despite their miniaturization trend (19), these devices are criticized for their bulkiness and rigidity. But in wrist arthroscopy, the surgical technique demands more freedom of movement and extension of instruments and of the optic device than for hip arthroscopy.

Electromagnetic localization devices do not have the drawbacks of both previously described localization devices. Unlike optoelectronic sensors, electromagnetic sensors can be localized even when they are concealed. Unlike mechatronic sensors, electromagnetic sensors are in the millimeter domain and linked to the localization device through flexible electrical cables. Both these advantages make electromagnetic localization devices more adapted for navigation in endoscopic surgery.

Navigation systems based on electromagnetic localization devices are already used in routine in ENT (20), thanks to various commercialized navigation stations (InstaTrak 3500 Plus®, General Electric Healthcare Surgery™, Lawrence, Massachusetts, USA; StealthStation® S7™ System, Medtronic Navigation™, Louisville, Kentucky, USA). The accuracy of these navigation systems can be compared to the accuracy of navigation systems based on optoelectronic localization devices (21).

Electromagnetic localization devices however have a few drawbacks.

Unlike optoelectronic localization devices using passive sensors, electromagnetic localization devices necessarily feature a connection cable between electromagnetic sensors and the control unit. The arthroscope and motorized instruments (shaver, milling tool) are also linked to the arthroscopy column through various cables (source of energy, cold light, water, aspiration). The palpator has also to feature an electromagnetic sensor with
a connection cable. In fact, associating or integrating the cable of the electromagnetic sensor to the entire cable set does not affect maneuverability of the arthroscope and the palpator.

Issues arising from the transmitter of the electromagnetic field have to be added to this first constraint. It is usually a box with a volume of about 1dm³, it is non-sterilizable and emits an efficient electromagnetic field within a cubic space with 50 cm sides. Incidentally, this volume perfectly integrates the operating field in wrist arthroscopy, which is limited to the dorsal side of the wrist. We therefore have to consider the introduction of the electromagnetic field of the transmitter into a sterile box fixed on or being part of the traction tower.

The main shortcoming of electromagnetic localization devices remains the lack of accuracy linked to distortion of the electromagnetic field due to the presence of ferromagnetic objects (traction tower, arthroscope, instruments). The accuracy of these devices has been commented in several studies (22-24). Yaniv et al. (7) explored in clinical conditions the accuracy of the Aurora® electromagnetic localization device, which we have used for our study, and they have found a mean squared error (MSE) of 1,01mm and 1,54° respectively for sensor position and orientation. These authors recommend as much as possible the exclusion or removal of ferromagnetic objects which may interfere with the electromagnetic field.

The problem of decreasing acuity of measures because of electromagnetic field distortion already crucially arose in the domain of intraoperative MRI. Non-ferromagnetic instruments have been developed to overcome that problem. They are made of plastic materials, ceramic, aluminum or titanium. Both last metals have a magnetic susceptibility respectively of $2 \times 10^{-5}$ and $2 \times 10^{-4}$, i.e. more than one million times less than magnetic susceptibility of iron. Since they are resistant and easy to sterilize, these materials have to be privileged for the design of arthroscopes, instruments and traction towers adapted to navigation systems based on electromagnetic localization devices.

Furthermore, in his PhD dissertation (Fischer GS. Electromagnetic tracker characterization and optimal tool design. MSE master’s thesis 2005. Johns Hopkins University, Baltimore), Fischer determined the optimum number, position and orientation of sensors fixed on the arthroscope and on the instruments in order to minimize the inaccuracy in the localization of these objects. For the arthroscope, he recommends to use two sensors, one placed in parallel to the arthroscope axis and the other one placed perpendicularly. He even imagines arthroscope integrated sensors (Fig. 6a). However, to minimize measurement inaccuracy of arthroscope axis rotation, the distance between
both sensors has to be small. He then imagines sensors integrated into a sleeve, which would be interdependent at the distal tip of the arthroscope (Fig. 6b).

In order to simplify the registration problem of oblique vision optics, we chose to block camera rotation around the axis of the optic device and to apply the method described by Tsai (12). However, Wu and Jaramaz (25) have described a registration method allowing to take the camera rotation around the axis of the optic device into account. The next development step for a navigation system dedicated to wrist arthroscopy will therefore have to take it into account.

The augmented reality view represents a valuable assistance when surgeons want to position the arthroscope or locate their instruments. It makes the maneuver more intuitive, increases comfort, saves time and enhances concentration. Preliminary results of our study allowed for the validation of the development feasibility of a navigation system using augmented reality for wrist arthroscopy. The research work has now to be continued to identify pedagogical and clinical applications.

**Figure 6a,b:** Diagram representing the optimum layout of arthroscope sensors according to Fischer, reproduced with the author’s agreement. (a) Arthroscope with two integrated sensors. The most distal sensor has to be the closest to the arthroscope tip to minimize the localization inaccuracy. (b) Sleeve with two integrated sensors that can be placed at the distal part of the arthroscope or instruments. The distance between the sensors has to be reduced to minimize the measurement errors of the arthroscope rotation axis.
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