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***Abstract*—Today, medical simulators are increasingly gaining appeal in clinical settings. In obstetrics childbirth simulators provide a training and research tool for comparing various techniques that use obstetrical instruments or validating new methods. Especially in the case of difficult deliveries, the use of obstetrical instruments—such as forceps, spatulas, and vacuum extractors—has become essential. However, such instruments increase the risk of injury to both the mother and fetus. Only clinical experience acquired in the delivery room enables health professionals to reduce this risk. In this context, we have developed, in collaboration with researchers and physicians, a new type of instrumented forceps that offers new solutions for training obstetricians in the safe performance of forceps deliveries. This paper focuses on the design of this instrumented forceps, coupled with the BirthSIM simulator. This instrumented forceps allows to study its displacement inside the maternal pelvis. Methods for analyzing the operator repeatability and to compare forceps blade placements to a reference one are developed. The results highlight the need of teaching tools to adequately train novice obstetricians.**

***Index Terms*—Childbirth simulator, instrumented forceps, medical robotics, medical simulators.**

I. Introduction

DESPITE significant progress in medical technology, the perinatal mortality rate in France has remained unchanged since the 1980s [1]. Obst *et al.* suggest this could result from traditional obstetrical training. The authors state, *"Medical students initially follow a purely theoretical period of training which directly leads to the practice in the delivery ward."* [2]

It remains difficult to prepare physicians for assisting in the various stages of childbirth because, as students, they lack access to effective haptic medical tools during their training. In obstetrics, forceps training is provided in the delivery room. There are two major constraints involved in obstetrical procedures: the lack of space and the lack of time. The workspace is the pelvic canal, therefore expert obstetricians cannot control the gestures performed by novice obstetricians. The time constraint results from the emergency nature of the procedure. Moreover, new constraints have compounded these two, decreasing the procedure's use [3] and the time dedicated to training novice obstetricians (European safety rules prohibit work the day after night duty) as well as tarnishing the image of forceps use in medicine [4].

To complete the training of novice obstetricians, there are currently several types of childbirth simulators, each characterized by their functionalities [5].

- Anatomical simulators generally make use of anthropomorphic manikins, often used in midwifery and medical schools.
- Virtual simulators make it possible to observe the path of the fetus through the pelvis [6]. Some of these simulators offer haptic feedback systems [7], [8].
- Instrumented anatomical simulators are much more attractive because they integrate the functionalities of both of the above types [9]–[13].

Today, there are no instrumented anatomical simulators offering complete training. The BirthSIM simulator has been developed to fill this gap. This new tool, coupled with our instrumented forceps, offers new solutions for teaching instrumental deliveries. In 2003, 11.2% of births in France required the use of obstetrical instruments (6.3% by forceps and 4.9% by vacuum extraction). A recent study performed in the French Rhone-Alps region demonstrated that inadequate training or the lack of experience in instrument handling during emergency procedures led to complications in 3.2% of births by instrumental delivery [14].

The possible tragic consequences of instrumental deliveries in these cases are related to problems in clinical obstetrics education. Only clinical experience informs the gestures needed to realize safe forceps delivery. No obstetrical manuals describe the forceps delivery path. Teaching and learning such gestures pose several challenges: it is *complex*, performed *blindly* within the pelvic canal (making it difficult to control), potentially *dangerous*, often carried out as an *emergency* procedure, and becoming increasingly *rare*. Some obstetricians may complete their training without having built the necessary hands-on, clinical experience to perform instrumental deliveries. The use of instrumented forceps, coupled with the BirthSIM simulator, addresses not only this training issue, but also ensures quality control of instrumental deliveries.

This paper highlights the design of the instrumented forceps used with the BirthSIM simulator. It is divided into three sections. The first presents the instrumented forceps and BirthSIM simulator. The second is dedicated to the method we developed to assess the competency of operators. The final section is devoted to the processing of results obtained from obstetricians' gestures during forceps deliveries. In conclusion, we present work now in progress as well as future projects.

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*R. Moreau is with the Laboratoire d'Automatique Industrielle (LAI), Institut National des Sciences Appliquées (INSA of Lyon), Villeurbanne 69621, France (e-mail: richard.moreau@insa-lyon.fr).

M. T. Pham, R. Silveira, T. Redarce, and X. Brun are with the Laboratoire d'Automatique Industrielle (LAI), Institut National des Sciences Appliquées (INSA of Lyon), Villeurbanne 69621, France.

O. Dupuis is with the Hospices Civils de Lyon (HCL) – CHU Lyon Sud – 69495 Pierre-Benite, France.

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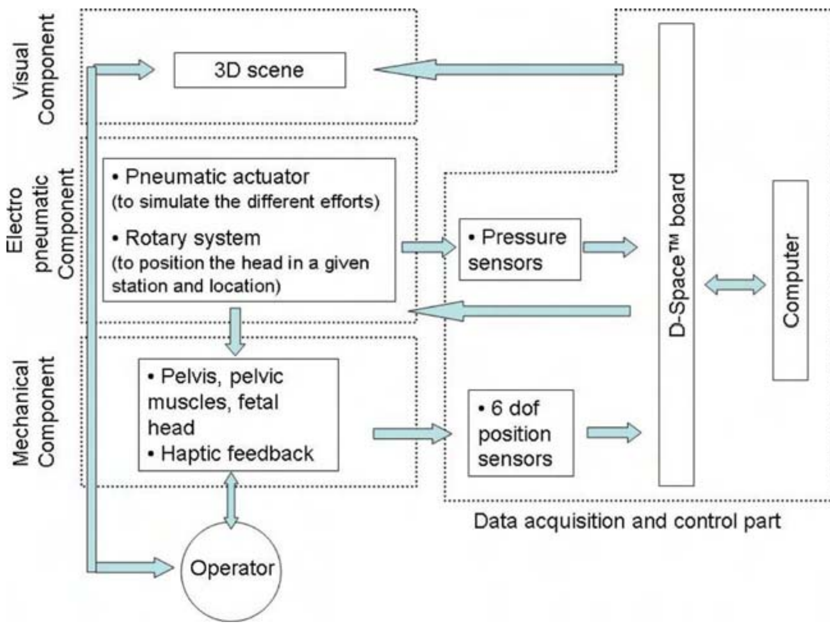

Fig. 1. Principle diagram of the BirthSIM simulator.

Fig. 2. The anthropomorphic models of the maternal pelvis and the fetal head. (a) The rebuilt silicone fetal head. (b) The pelvic model with its anatomical references: coccyx, sacrum, ischial spines, and pubis.

II. Instrumented Forceps Dedicated to Training Obstetricians

A. BirthSIM Simulator Mechanical Component

To validate this new instrumented forceps, we used the BirthSIM simulator [15], [16]. It consists of three components: mechanical, electropneumatic, and visual (Fig. 1). To evaluate the paths of the instrumented forceps, we used only the mechanical component.

The BirthSIM simulator mechanical component consists of anthropomorphic models of the maternal pelvis and the fetal head. A 3-D model of the cranium of a fetus was obtained from medical scans provided by the hospital. Then, through rapid prototyping, we constructed a cranium and molded a silicone head. The head bears the main anatomical landmarks (fontanels, sutures, ears), allowing realistic examination of the fetal head [see Fig. 2(a)].

The pelvic model was manufactured by Simulaids Corporation [17]. It accurately reproduces the maternal pelvis, with its particular anatomical landmarks: ischial spines, pubis, coccyx, and sacrum [see Fig. 2(b)]. This allows obstetricians to train through haptic simulation mirroring real delivery.

With this simulator, a medical professional can palpate the expected landmarks and make transvaginal assessment diagnosis [18]. This determines the fetal presentation inside the pelvis. The fetal head presentation is given by two parameters: fetal head **station** and **location**. The **station** is the distance of the head from the ischial spines, from $-5\ \mathrm{cm}$ to $+5\ \mathrm{cm}$, as defined by the American College of Obstetricians and Gynecologists. A station of $+5\ \mathrm{cm}$ corresponds to the moment when the fetal head is at the level of the vaginal introitus. Obstetrical instruments in deliveries are only used if the fetal head is in front of the ischial spines (from 0 to $+5$ station). The **location** concerns the orientation of the fetal head around the axis of the pelvic canal. Traditionally, eight different positions (every 45°) are used to describe fetal head orientation.

B. Instrumented Forceps

Forceps have been used for more than 400 years, but only during the last 70 years has there been several research studies to measure the forces linked with their use. Several studies have been undertaken to quantify the tractive effort to apply during instrumental deliveries. For example, forceps have been equipped with a dynamometer [19], strain gauges [20], [21] and analyzed through theoretical calculations based on the maximum pressure of the amniotic liquid in the second phase of labor [22]. The results were quite varied and inconclusive; the maximum tractive force ranged from 150 to 300 N. In addition, some researchers have attempted to quantify the compressive forces applied to each side of the fetal head by instrumenting a forceps with optical fiber sensors [23]. Along the same lines, Moolgaoker used water-inflatable sensors to study the compressive forces applied by various types of forceps and vacuum extractors [24], [25]. He showed that the total compressive and tractive forces were weaker for forceps compared to vacuum extractors.

Finally, a recent study focused its analysis on the area of the fetal head acted on by the forceps. Dupuis developed the concept of quality forceps blade placement (FBP) [26]. His theory

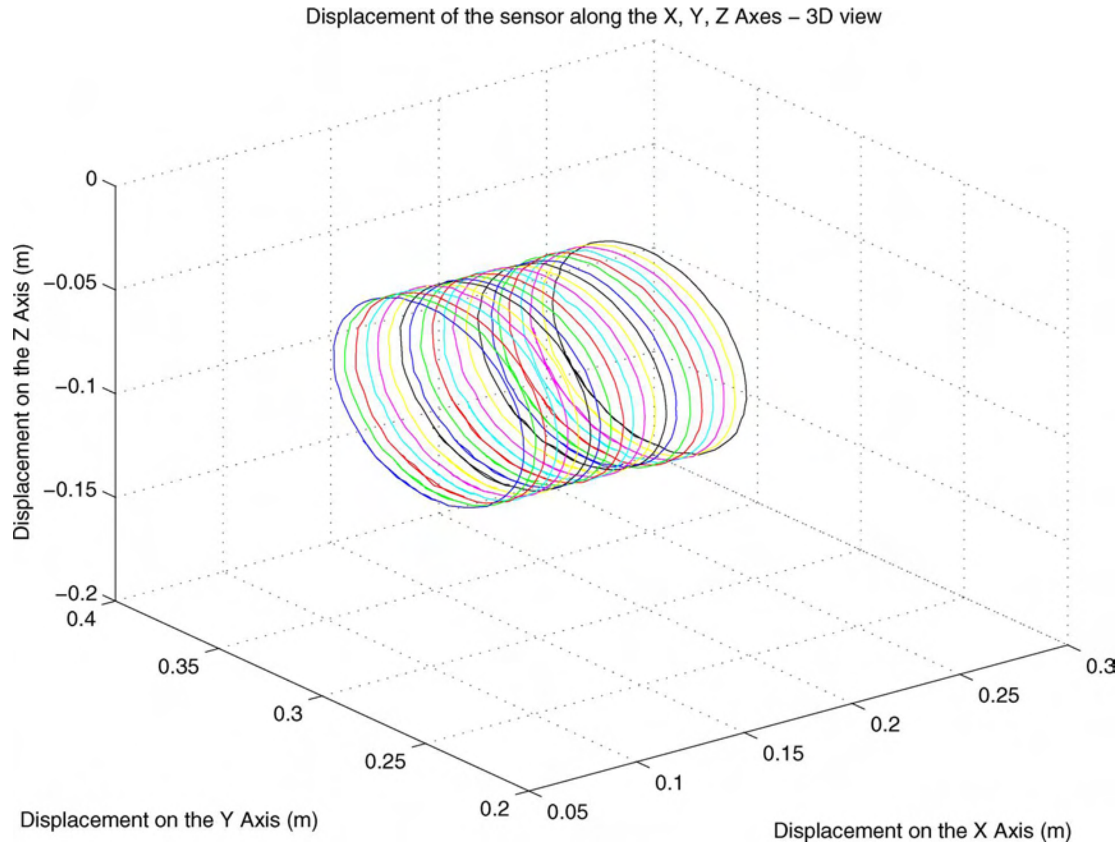

Fig. 3. Measurements of the sensor displacement on separated circles of 0.5 cm along the $\overrightarrow{x}$-axis.

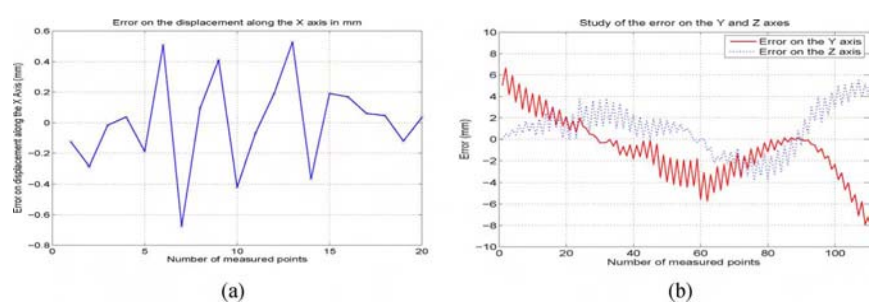

Fig. 4. Sensor errors along the three axes. (a) Sensor static errors along the $\overrightarrow{x}$-axis. (b) Sensor dynamic errors along the $\overrightarrow{y}$- and $\overrightarrow{z}$-axes.

is based on this principle: a significant force applied symmetrically is safer than a weaker force applied asymmetrically. Thus, we developed an instrumented forceps in order to measure forceps displacements.

C. Miniaturized Position Sensors

The originality of the instrumented forceps is that it makes it possible to study forceps paths inside the pelvis, allowing the medical team to understand FBPs more clearly. To monitor the simulator's various components, several challenges had to be overcome: the restricted workspace and obscuring of some objects means they cannot be monitored inside the pelvis. We chose a system using electromagnetic sensors that can follow masked objects. These sensors have six degrees of freedom (DOFs) (position and orientation).

We chose the MiniBird [27] system of measurement, developed by the company Ascension. It measures, in real time, the position and orientation of one or several miniaturized sensors. These sensors measure the impulse of the magnetic field emitted by a box called a transmitter. Three factors must be taken into account when using such a system: the presence of ferromagnetic materials in the measurement field can disrupt measurements; the measurement field is limited in size; and the 120 Hz sampling rate is divided by the number of sensors used. Since we are using three sensors (one in the fetal head and one in each forceps blade), the sampling rate is 40 Hz. This frequency is compatible with classic childbirth. The measurement field dimension of the sensors (a 80-cm diameter half-sphere) is sufficient because data acquisition takes place inside or beside the maternal pelvis.

We calibrated the sensors in order to check their accuracy and the influence of the simulator's ferromagnetic materials on the measurements. The fetal head was then moved inside the pelvis to reproduce the different head stations and locations. For each

Fig. 5. Instrumented forceps with sensors.

station, the head was moved through the different locations, thus delineating a circle. This experiment was repeated throughout the twenty centimeters, which corresponds to the maximum displacement of the fetal head in the maternal pelvis. The fetal head's workspace is shown in Fig. 3 where the $\overrightarrow{x}$-axis rests along the pelvic canal.

The software, Control Desk [28], provided with a dSPACE acquisition board, collected the sensor data (Fig. 1). Fig. 4(a) shows the static errors revealed along the $\overrightarrow{x}$-axis. The $\overrightarrow{y}$-axis corresponds to the transversal axis, while the $\overrightarrow{z}$-axis corresponds to the vertical axis. To control the errors along the $\overrightarrow{y}$- and $\overrightarrow{z}$-axes, the circular paths are compared with perfect circles. This experiment was carried out while the fetal head was in motion. The worst dynamic errors are shown graphically in Fig. 4(b). From a medical point of view, the BirthSIM simulator should guarantee accurate positions to within one centimeter; in our case, the maximum error obtained was less than one centimeter, allowing us to conclude that the error is insignificant.

To analyze FBP, a forceps was instrumented with position sensors (Fig. 5). To avoid interference in the measurements of the magnetic sensors, all the simulator elements must be nonmagnetic. However, traditional forceps used in delivery rooms are composed of magnetic, stainless steel material. Therefore, it was necessary to manufacture forceps using nonmagnetic material. To construct a realistic simulator, we had to choose material that weighs approximately the same as that used in today's hospital forceps, meaning 661 g for Levret's forceps. Bronze, in addition to being nonmagnetic, has a density similar to stainless steel. We, therefore, molded bronze forceps, whose mass is 774 g. Coupled with the BirthSIM simulator, this is the first instrument developed to measure the displacements of forceps blades during their use. The sensors allow us to ensure the repeatability of our experiments. By fixing the transmitter to the maternal pelvis, we can accurately reproduce fetal head presentation.

D. *Study of the Paths During Forceps Blade Placement*

The BirthSIM simulator enables the paths of the forceps during its placement to be studied. In studying the paths, the most interesting point to follow is the tip of the blade (the point P in Fig. 6). This is the part of the forceps in permanent contact with the fetal head; it must surround the head to take position behind the fetal ears. However, the sensors, with six DOFs (the

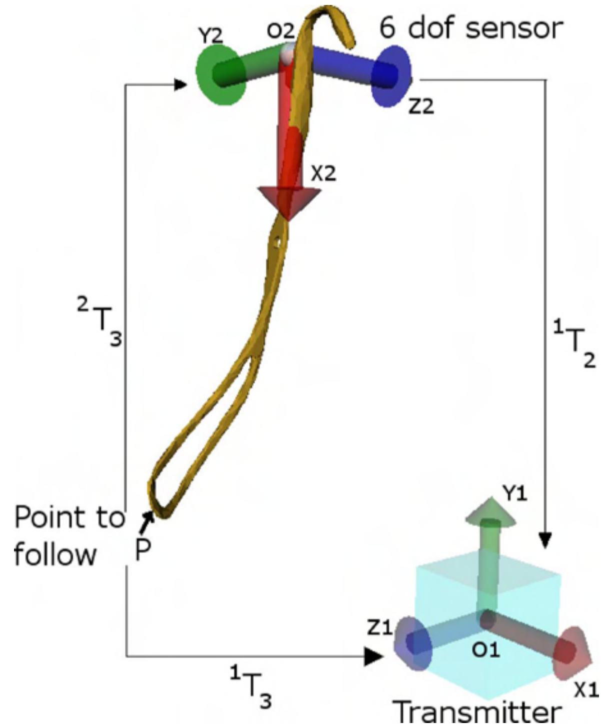

Fig. 6. Different frames associated with the forceps.

3 positions (x, y, and z) and the 3 orientations (θ, ϕ, and ψ) of the sensors with respect to the transmitter frame which is also the world frame), are located at the opposite tip of each blade, as show in Fig. 5. Fig. 6 represents the different frames associated with one forceps blade. Frame 1 corresponds to the world frame of the simulator, while frame 2 is attached to the sensor. Since the most interesting point to follow is the tip of the forceps blade, we have carried out a frame transformation to establish the coordinates of tip P with respect to frame 1

$$^1T_2 = \begin{bmatrix} & {}^1R_2 & & (O_1O_2)_{x_1} \\ & & & (O_1O_2)_{y_1} \\ & & & (O_1O_2)_{z_1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$^2T_3 = \begin{bmatrix} & {}^2R_3 & & (O_2P)_{x_2} \\ & & & (O_2P)_{y_2} \\ & & & (O_2P)_{z_2} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$^1T_3 = {}^1T_2{}^2T_3 \quad (3)$$

where

- point O_1 is the origin of the world frame (center of the transmitter);
- point O_2 is the position of the sensor;
- point P is the forceps tip that will be monitored;
- $^iR_{i+1}$ is the rotation matrix from frame i to frame $i+1$ ($i = 1, 2$);
- and $^iT_{i+1}$ is the homogeneous transform matrix from frame i to frame $i+1$ ($i = 1, 2$);

$^1T_2$ allows to know the position of O_2 in frame 1 as defined by (O_1, $\overrightarrow{x_1}$, $\overrightarrow{y_1}$, $\overrightarrow{z_1}$). This homogeneous transform matrix is directly given by the sensors. Sensors give us the position and orientation of O_2 (center of frame 2) in frame 1. $(O_1O_2)_{x_1}$

($(O_1O_2)_{y_1}$ and $(O_1O_2)_{z_1}$, respectively) corresponds to the x (y and z, respectively) coordinate of (O_1O_2) in frame 1 [see (1)].

${}^2T_3$ allows to know the position of P (forceps blade tip) in frame 2 as defined by (O_2, $\overrightarrow{x_2}$, $\overrightarrow{y_2}$, $\overrightarrow{z_2}$). This homogeneous transform matrix is given by the forceps blade geometry, which is accurately known. $(O_2P)_{x_2}$ ($(O_2P)_{y_2}$ and $(O_2P)_{z_2}$, respectively) corresponds to the x (y and z, respectively) coordinate of (O_2P) in frame 2 [see (2)].

By multiplying ${}^1T_2$ by ${}^2T_3$ [see (3)], ${}^1T_3$ is obtained, allowing to know the position of P in frame 1 directly. Thus, we know the position of the forceps blade tip (point P) in real time in the world frame of the simulator (Fig. 6)

E. Experimental Protocol

The head is positioned at **LOA+5** (**L**eft **O**ccipito **A**nterior **location** and **+5 cm station** from the ischial spines plane), corresponding to a "quite difficult" forceps delivery. The operator examines the pelvis and must locate the anatomical (ischial spines, pubis, sacrum, and coccyx) and fetal head (ears, sutures, and fontanels) landmarks. Eight operators with different levels of expertise (four experts and four novices) were selected from the Croix-Rousse Hospital staff to carry out FBPs for analysis. An expert obstetrician is defined as having had ten years of experience, using forceps in more than 80% of interventions. A novice is a young obstetrician with less than 12 mo. of obstetrical experience. Each operator performed four FBPs, the first to get used to the simulator and the last three for experimental recording. Each blade path is recorded separately, first the left blade, then the right blade.

The first factor to analyze involved measuring forceps paths to evaluate the repeatability of each operator's obstetrical technique, according to the operator's experience. The second factor concerns comparing the paths to a reference movement that has been averaged from expert paths for a given fetal head station and location.

III. Methods

A. Paths Analysis for Medical Gestures

Medical gestures have often been studied in order to design medical robots or improve medical techniques. Several fields of medicine are implicated in such studies, including surgery, dermatology, orthopedics, and radiology. Studies of medical gestures are based on the techniques of experts and measure their movements according to different parameters.

1) Studies based on observing expert tasks and gestures and describing and analyzing them qualitatively. This kind of study can be complemented with studies based on force and movement sensors. Studies of expert and novice surgeons, using video analysis, were carried out during a laparoscopic surgical procedure [29]. Using the same methods, ultrasonography gestures have been previously described [30].
2) Studies based on measuring medical instruments equipped with sensors. This kind of study is more common and produces quantitative data. Sensors measure the forces and torques applied by a surgeon and also provides a complete description of the movement (trajectory, range, displacement, and velocity). Forces and torques involved during endoscopic gestures can be quantified using hidden Markov models [31], and measure scalpel velocity during skin harvesting [32] or ultrasonography instrument displacement [33].
3) Studies based on measuring specific instruments. Passive mechanisms for holding medical instruments are designed to measure the instruments' displacements. The BlueDRAGON system is used to study two endoscopic tools [34].

In our case, we analyzed the paths of forceps instrumented with motion sensors. These sensors enable FBP to be studied. Video analysis was not possible because the gestures mainly take place inside the pelvis, where they cannot be monitored. New methods have been developed to characterize obstetrical gestures and compare the know-how and skill of operators.

B. Evaluation of Gesture Repeatability

The time obstetricians take to position the forceps, within reasonable limits, is not a primary importance in the majority of the case, considering that Caesarean sections are more time-consuming. The main goal is to position the forceps correctly. Since time is not a crucial factor during FBPs, we analyzed paths, rather than trajectories. Taking into account the complexity of paths in space, forceps blade paths are characterized by three specific points: the *departure point* is the point of contact with the fetal head from which the operator begins the gesture; the *return point* is the deepest point in the maternal pelvis in the frontal plane, also corresponding to a maxima position along the $\overrightarrow{y}$-axis and the *arrival point* is the final point of the gesture.

We have developed a method to compare these paths. It is based on considering each specific point as a member of a theoretical sphere, as follows:

- a departure sphere corresponding to the smallest sphere that gathers all the departure points of the paths;
- a return sphere corresponding to the smallest sphere that gathers all the return points of the paths;
- an arrival sphere corresponding to the smallest sphere that gathers all the arrival points of the paths.

To compare the different radius values, five degrees of repeatability were arbitrarily defined as follows:

- *excellent* if the sphere radius, r, is ≤ 0.5 cm;
- *very good* if the sphere radius, r, is between 0.5 cm and 1 cm inclusive;
- *good* if the sphere radius, r, is between 1 cm and 1.5 cm inclusive;
- *poor* if the sphere radius, r, is between 1.5 cm and 2 cm inclusive;
- *very poor* if the sphere radius, r, is > 2 cm.

This method establishes whether an operator can place forceps in the same position several times. The smaller the spheres are, the more repeatable the movement of the operator is. Visual qualitative analysis is ensured with regard to the paths within the spheres. For quantitative analysis, the degree of repeatability of the operator is defined by the values of the radii.

C. Comparison to the Reference Placement

This second method relies on calculating the error between the recorded paths and a reference path, based on the techniques of experts. Expert paths are considered correct in the placement

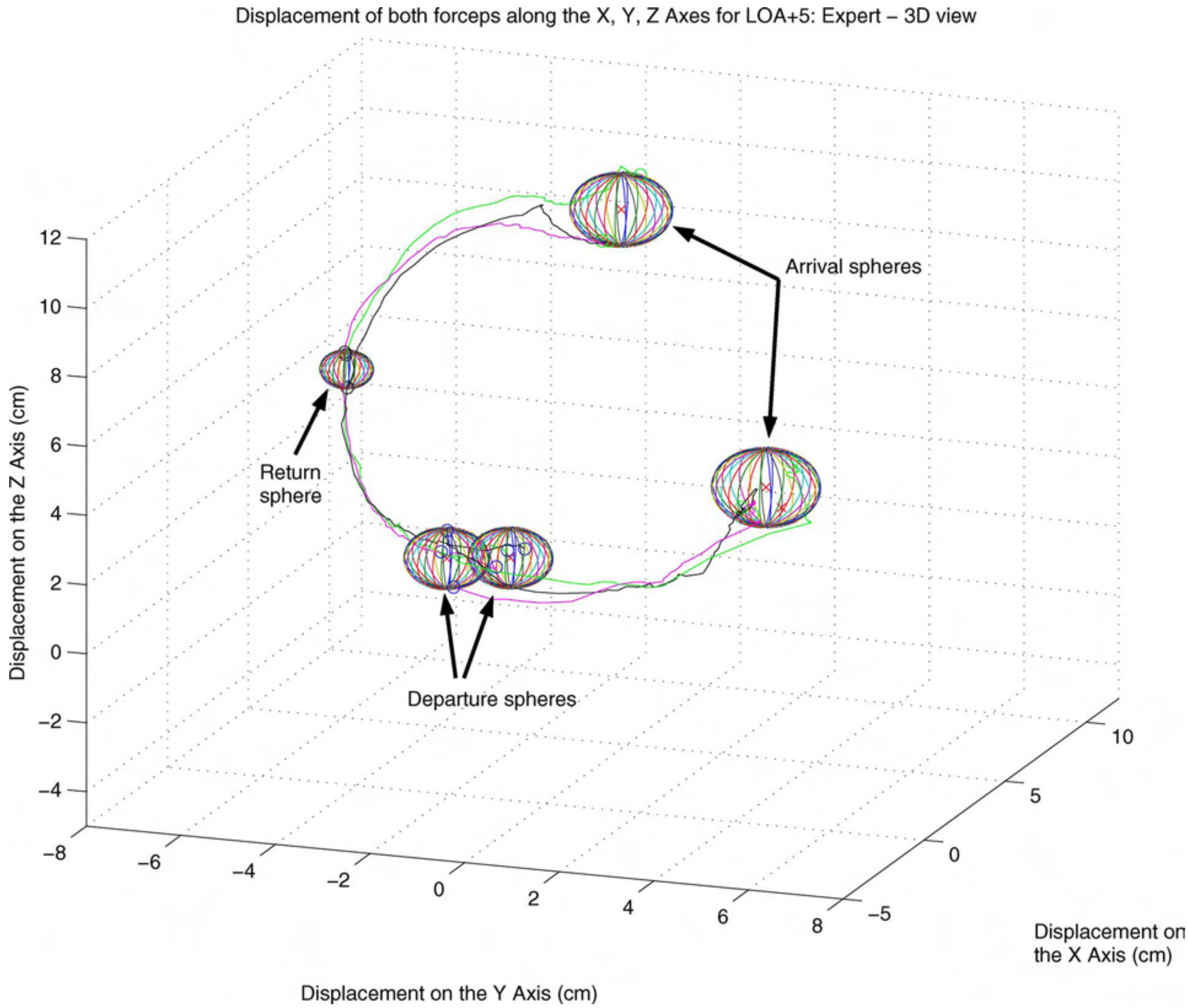

Fig. 7. Expert paths of the forceps with the spheres.

of forceps. To obtain the reference path, it was necessary to calculate the average of several expert paths. Because expert operators require different amounts of time to place forceps, vectors of data had to be normalized to obtain a consistent data sample. This average data sample was calculated from all the expert measurements.

Normalization enables the paths of different operators to be compared with the reference path. The comparison is based on the results of calculating the integral of the error along the three axes

$$\varepsilon_x = \int_0^{t_f} |x_{\mathrm{ref}}(\tau) - x_{op}(\tau)|\, d\tau \tag{4}$$

$$\varepsilon_y = \int_0^{t_f} |y_{\mathrm{ref}}(\tau) - y_{op}(\tau)|\, d\tau \tag{5}$$

$$\varepsilon_z = \int_0^{t_f} |z_{\mathrm{ref}}(\tau) - z_{op}(\tau)|\, d\tau. \tag{6}$$

Because we are mainly interested in the whole path, we summed the three errors

$$\varepsilon = \varepsilon_x + \varepsilon_y + \varepsilon_z. \tag{7}$$

where t_f is the time the operator needed to position the forceps, x_{ref} (y_{ref} and z_{ref}, respectively) is the blade displacement along the $\overrightarrow{x}$-axis ($\overrightarrow{y}$ and $\overrightarrow{z}$, respectively) of the reference movement and x_{op} (y_{op} and z_{op}, respectively) is the blade displacement along the $\overrightarrow{x}$-axis (the $\overrightarrow{y}$ and $\overrightarrow{z}$, respectively) of the operator whose path we want to compare.

By defining the average expert path as the reference path, this method enables the differences between operators to be quantified.

IV. Results

A. *Measurement of Operator Repeatability*

In Fig. 7 we observe the paths of the forceps tip when the fetal head is at **LOA+5**. The spheres represent the smallest spheres that include the departure, return, and arrival points for the left and right blades. Comparisons can be made visually based on the size of the different spheres. On this figure only the results of one expert with three different FBPs are represented.

We see that there is no return sphere for the left blade path because there is only one direction during its placement. In fact the left blade has a direct path whereas the right blade has a more complicated path with a large rotation due to the orientation of the fetal head inside the pelvis. Because this gesture is

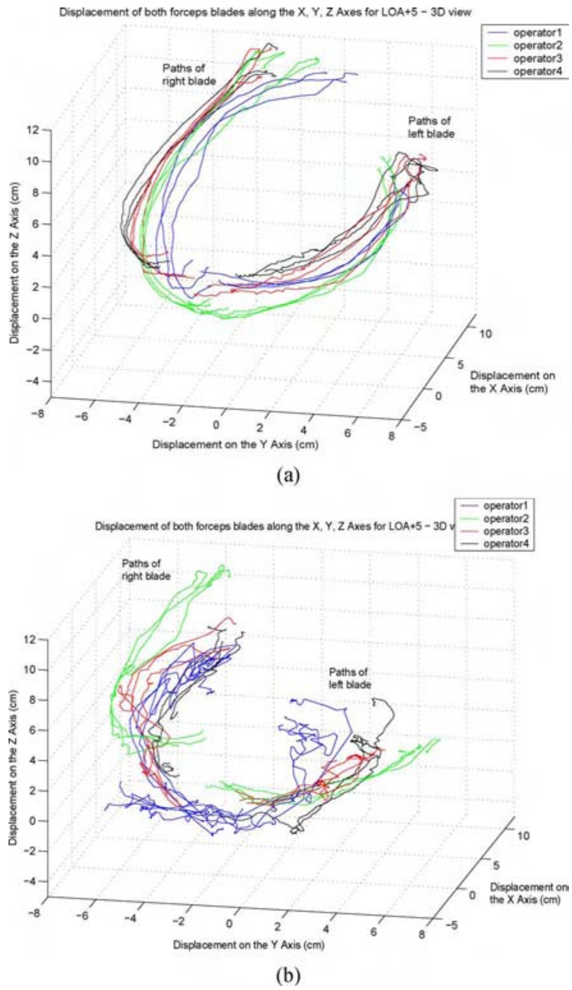

Fig. 8. Paths of the forceps blade tips for experts (a) and for novices (b).

asymmetrical between the two blades, the obstetrical gesture is difficult to carry out and thus to teach and to learn.

To complete the visual analysis of the spheres, we visualize the paths taken by different experts [Fig. 8(a)], which correspond to that of the forceps blade tips. These plots show the three analyzed paths of four experts, as defined in the experimental protocol (Section II-E). For increased clarity, the spheres that gather specific points (departure, return, and arrival) are not shown.

The subjective analysis of this movement shows a high degree of visual consistency between the experts. On the other hand, when we observe the plots of novices, we notice differences, including, most importantly, greater variance between operators [Fig. 8(b)].

In Table I we see the radii of the different spheres according to the operator and forceps blade. The radii are expressed in centimeters.

First, we note larger values for some radii in the novice table compared to the expert table. To illustrate these differences, Table II shows the number of *excellent*, *very good*, *good*, *poor*, and *very poor* spheres, according to their radii and the five degrees of repeatability, as defined in Section III-B; it also displays their percentages. We note that, for all operators and both blades, there were 0% *excellent* spheres, confirming the difficulty of the gestures. Moreover, we also note that 75% of the gestures performed by experts have a radius inferior to 1.5 cm for the left blade and 92% for the right. On the other hand, novices do not achieve this level of satisfactory results; the radius values are greater. Only 50% of novices obtain spheres with a radius less than 1.5 cm for the left blades and 58% for the right.

TABLE I
TABLE OF THE SPHERE RADII IN CENTIMETERS

Station and location LOA+5		Experts		Novices	
		Left blade	Right blade	Left blade	Right blade
Operator	Sphere				
1	Departure	0.95	0.64	2.15	2.42
	Return	-	1.76	-	1.43
	Arrival	0.67	0.98	1.70	1.70
2	Departure	0.75	0.67	0.66	2.75
	Return	-	0.61	-	0.91
	Arrival	1.71	1.09	0.70	0.90
3	Departure	1.07	1.03	0.59	0.84
	Return	-	1.19	-	1.95
	Arrival	0.94	1.06	1.91	1.16
4	departure	1.92	0.60	2.61	2.44
	Return	-	1.63	-	1.11
	Arrival	1.73	0.93	1.42	0.91

TABLE II
RESULTS IN PERCENTAGE ACCORDING TO THE CRITERION OF REPEATABILITY WHERE n IS THE NUMBER OF SPHERES

Station and location LOA+5	Experts				Novices			
	Left Blade		Right Blade		Left Blade		Right Blade	
	n	%	n	%	n	%	n	%
Excellent	0	0	0	0	0	0	0	0
Very Good	5	62	7	58	3	37	4	33
Good	1	13	4	34	1	13	3	25
Poor	2	25	1	8	2	25	2	17
Very Poor	0	0	0	0	2	25	3	25

B. Results for the Comparison to a Reference Gesture

For this study, the fetal head remained at **LOA+5**. Fig. 9 represents the errors, compared to the reference path, of one expert for all the three FBPs he made. For a better visibility, the results of only one expert are shown on this figure, but similar results were obtained for the others as shown in Table III.

Fig. 10 shows the errors compared to the reference path of one novice for all the three FBPs he made. For a better visibility, the results of only one novice are shown on this figure, but similar results were obtained for the others as shown in Table III.

Table III shows the average errors for three measurements of operators (four experts and four novices). Because the gesture is asymmetrical, the left and right blades must be distinguished. The results give the projected errors on the $\overrightarrow{x}$-, $\overrightarrow{y}$-, and $\overrightarrow{z}$-axes as well as their sum ε [see (7)].

This table highlights the similarity of the results between different operators. The average error for all novices is 27.12 for the left blade and 35.95 for the right. For experts the average error is 11.38 for the left blade and 21.02 for the right.

V. DISCUSSION

A. Clinical Discussion

One novel feature of the BirthSIM simulator is that it offers, for the first time, the possibility of checking the quality of FBP

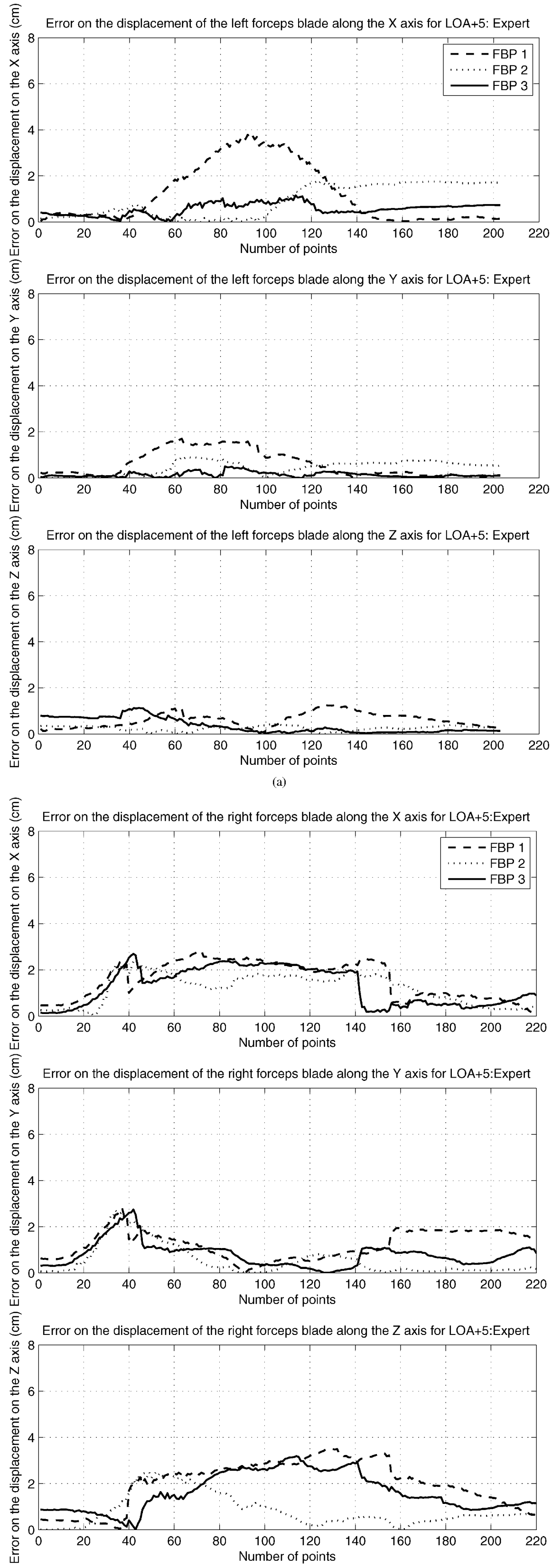

Fig. 9. Errors of an expert during the FBP along the $\overrightarrow{x}$, $\overrightarrow{y}$ and $\overrightarrow{z}$ axes. (a) Left blade error during its placement. (b) Right blade error during its placement.

and quantifying the gap between experts and novices with respect to that placement. The analysis was realized only for station and location **LOA+5**. With this study, we confirmed our previous results [35] for station and location **OA+5** (Occipitoanterior location at $+5$ station). For both presentations, novices do not have the same ability to place forceps to a sufficient degree of repeatability, meaning they need additional training before performing real instrumental deliveries.

TABLE III
RESULTS OF THE ERROR ALONG THE THREE AXES FOR EXPERTS AND NOVICES COMPARED TO THE REFERENCE PATH.

Station & Location LOA+5		Left blade			
		ε_x	ε_y	ε_z	ε
Expert	1	7.09	3.15	3.33	**13.57**
	2	4.53	2.03	2.03	**8.60**
	3	5.44	2.09	2.15	**9.68**
	4	8.87	2.00	2.79	**13.66**
	Average				**11.38**
		Right blade			
		ε_x	ε_y	ε_z	ε
Expert	1	5.54	13.44	9.71	**28.69**
	2	7.84	5.49	9.08	**22.41**
	3	5.58	4.19	7.28	**17.05**
	4	4.80	3.61	7.53	**15.94**
	Average				**21.02**
		Left blade			
		ε_x	ε_y	ε_z	ε
Novice	1	11.01	13.55	7.63	**32.19**
	2	11.96	9.20	4.00	**25.16**
	3	16.98	5.83	4.62	**27.43**
	4	8.93	7.31	7.44	**23.68**
	Average				**27.12**
		Right blade			
		ε_x	ε_y	ε_z	ε
Novice	1	10.37	5.86	17.65	**33.89**
	2	22.52	9.99	11.85	**44.36**
	3	12.47	8.11	15.80	**36.38**
	4	7.98	8.75	12.49	**29.19**
	Average				**35.95**

This new method allows to analyze the repeatability of an operator's technique. From this analysis, different levels of difficulty can also be highlighted during the placement. For example, the return point appears harder to achieve than the departure and arrival points. Experts achieve excellent, very good, and good results for their departure, return, and arrival points (75%, 50%, and 50% of the cases, respectively), while novices reach 37.5%, 37.5%, and 25%. These results are close to observations in the delivery room. Most forceps delivery failures occur when changing directions during FBP, corresponding to the return point.

Compared to the study of gestures for station and location OA+5 [35], the station and location, LOA+5, results in a more difficult gesture. Indeed, in the first case, experts achieved excellent, very good, or good results in 100%, 87.5% and 87.5% of cases for departure, return, and arrival, respectively. Novices achieved excellent, very good, or good results in 50%, 50%, and 12.5% of cases for departure, return, and arrival, respectively. Moreover, none of the operators realized excellent results for LOA+5, whereas, for OA+5, 25% of FBPs were excellent. Another difference between the two gestures must be noted and concerns the differences between the two forceps blades. For OA+5, there is no difference in the results (92% for both blades), while, for LOA+5, a difference was revealed (75% for the left blade and 92% for the right). Whatever the experience of the operators, their degree of repeatability is lower.

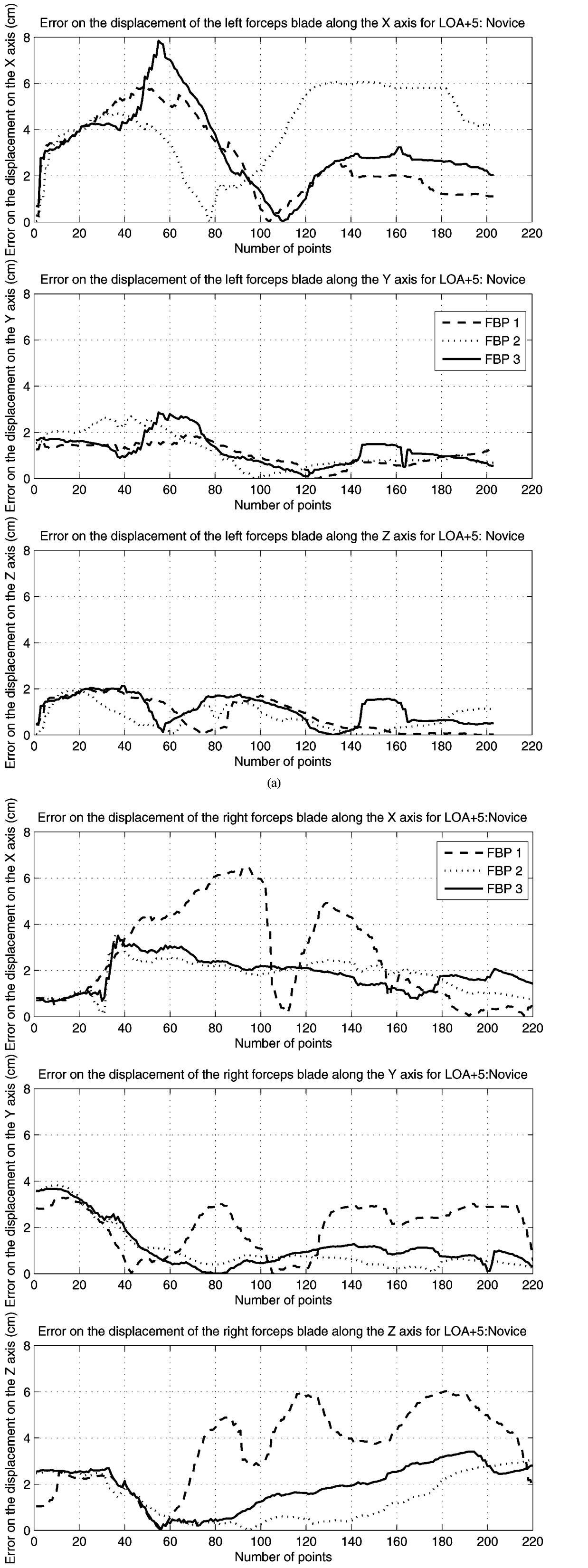

Fig. 10. Errors of a novice during the FBP along the $\overrightarrow{x}$, $\overrightarrow{y}$ and $\overrightarrow{z}$ axes. (a) Left blade error during its placement. (b) Right blade error during its placement.

When comparing operator paths with the reference path, the new method made it possible to demonstrate that expert paths are very close to the reference path along the three axes, while novice paths are farther (Figs. 9 and 10). Novice errors reach 8 cm with respect to the reference path, while expert paths do not exceed 3 cm, except for some points for the left forceps blade along the $\overrightarrow{x}$-axis.

Table III also shows the differences between the left and right forceps blades and between experts and novices. For experts, the error is smaller than for novices. So, an expert is able to follow the reference path, whereas a novice has more difficulty placing the forceps correctly. This difference is even greater for the right blade (27.12 for the left blade and 35.95 for the right). In fact, the right blade is considered more difficult to place for location, LOA, because its path has a complex rotation. Even experts have more difficulty placing the right blade: 11.38 for the left blade and 21.02 for the right. Those plots confirm one of the first results: the return point seems to be the hardest to master. The main errors appear at the middle of the right forceps blade paths, approximately where the return points take place. This method allows to quantify the overall difference between two gestures.

B. Path Analysis Discussion

For repeatability, we analyzed only three points in the complete paths of the operators. These three points represent crucial points along the path. The departure and arrival points enabled us to study FBP. The return point corresponds to a direction change in the forceps movement. It is mainly at this point that the operator risks injuring the soft tissues of the maternal pelvis or fetal head. Therefore, to study the repeatability of the movement, we chose to compare only these three points that characterize the paths. Using this method, the paths were analyzed without taking into account time and, therefore, were not modified. This method enables analysis of obstetricians' repeatability. Thus, we can demonstrate that experts reach a higher degree of repeatability than novices.

With regard to the reference gesture, the comparison is based on the entire path and not just the three points. However, to compare different paths, data must be modified according to the duration of the gestures. We had to normalize some paths so the time needed to place forceps would become a parameter for comparison. The error calculation is influenced by the required time. This method, however, makes it possible to study the path globally. Regarding the time needed to place forceps, the gap between experts and novices is quite small. Experts need an average of 4.29 s to place the left blade and 6.93 s for the right, whereas novices need 6.57 s for the left blade and 8.27 s for the right. Normalization does not greatly change the data. These results highlight the differences between experts and novices. Experts match the reference path more closely than novices. Moreover, because of the difficulty of the forceps procedure using asymmetrical paths for the forceps blades, the results also indicate the following distinction: the right anterior forceps blade is significantly more difficult than the left posterior one.

We note that only 12 FBPs were used to calculate the reference path (3 FBPs by 4 experts). This reference path is probably not statistically representative for these obstetrical gestures, but it was not possible to carry out additional experiments that include more hospital obstetricians.

With these two methods, we precisely studied obstetrical gestures according to two factors: repeatability and performance compared to a reference gesture. A more complete study is in progress in collaboration with the Croix-Rousse Hospital in order to obtain more significant results with a larger population. These first results show that the BirthSIM simulator, coupled with our instrumented forceps, makes it possible to quantify the know-how and skill of obstetricians and underscore the need for adequate training of novices.

VI. Conclusion and Furtherworks

This paper presents the design of a new instrumented forceps. Coupled with the BirthSIM simulator, this new device enables the study of FBP for the first time. Two criteria have been developed. We used the first to evaluate the degree of repeatability of an operator's technique and the second to quantify the differences between one placement and a reference placement.

The results highlight the difficulty in safely placing forceps. Novice obstetricians are unable to place forceps in the same manner several times, whereas experts demonstrate greater consistency in performing the same gesture a number of times. This difference increases with the difficulty in FBP. A previous study [35] showed the results for OA+5, while our present study revealed results for a more complex gesture (LOA+5). To some extent, the more complex the placement path, the more errors novices make.

During traditional training, novices must face these difficulties during actual deliveries, which can easily lead to tragic errors. To avoid such outcomes, we have developed this instrumented forceps to complement traditional training. Thus, novices can now gain experience performing the most difficult procedures using the BirthSIM simulator.

Currently, several studies using the BirthSIM simulator and its instrumented forceps are in progress or planning. Thanks to the BirthSIM simulator's visualization interface, we are currently developing a new method of training novices in order to evaluate their progress when using these new tools. They should be able to learn how to perform the reference gesture. This instrumented forceps will allow novices to train correctly prior to participating in actual instrumental deliveries. Experts will also be able to check the skills of novices by analyzing their progress on the simulator. A more comprehensive study of a larger population of novices should be carried out to produce more statistically significant results.

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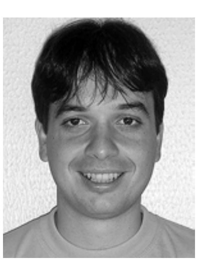
Richard Moreau received the M.E. in mechanical engineering from the Institut National des Sciences Appliquées (INSA) de Lyon, Lyon, France and the M.S. in biomechanical engineering from the University Claude Bernard de Lyon (UCBL), Lyon, France, in 2004. Since he is working towards the Ph.D. degree in the Laboratoire d’Automatique Industrielle (LAI), INSA de Lyon, in medical robotics area.

Minh Tu Pham received the M.E. in electrical engineering in 1998, the M.S. and Ph.D. degrees in control engineering from the University of Nantes, Nantes, France in 1998 and 2001, respectively.

He joined the Laboratoire d’Automatique Industrielle (LAI), Lyon, France, in 2003 and is currently Assistant Professor at the Mechanical Engineering Design Department, Institut National des Sciences Appliquées (INSA), Lyon, France. His research interests include robot identification, control, and the applications to medical robotics.



Ruimark Silveira was born in João Pessoa, Brazil, in 1978. He received the Ph.D. degree in industrial automatic from the Institut National des Sciences Appliquées (INSA) de Lyon, Lyon, France, in 2004.

His research has included biomedical engineering in obstetric area, with the use of the birth simulation and instrumented forceps for training young obstetricians.

Tanneguy Redarce received the Ph.D. degree in electrical engineering from the Institut National Polytechnique de Grenoble (INPG), Grenoble, France, in 1984. He received the Habilitate Doctor level from the Institut National des Sciences Appliquées de Lyon (INSA), Lyon, France, in 1995.

He was Assistant Professor for 15 years in the Mechanical Engineering Department, INSA de Lyon, and then Professor in the Electrical Engineering Department. He teach automatic control and Industrial Informatic. In 1999, he was a visiting Researcher at the Laboratoire d’Imagerie, de Vision et d’Intelligence Artficielle (LIVIA) de l’Ecole de technologie Supérieure de l’Université du Québec in Montréal, QC, Canada. Since 2000 he is at the head of the laboratory’s robotics research team. His interests include medical robotics, mechatronics systems, and robotic vision. He has published more than 100 papers in various journals and conferences.

Xavier Brun was born in France in 1973. He received the Ph.D. degree from the INSA Lyon Scientific and Technical University, Lyon, France, in 1999.

Since 2001, he is an Associate Professor with the Laboratoire d’Automatique Industrielle (LAI), Institut National des Sciences Appliquées de Lyon (INSA). His current interests concerns the implementation and comparison of controls laws for fluid power applications.

Olivier Dupuis was born in Prades, France, in 1966. He received the M.D. degree from the Paris V University Hospital, Paris, France, in 1999, specialized in obstetrics and gynecology (ObGyn), received the Ph.D. degree from Lyon INSA University Claude Bernard, Lyon, France, in 2005.

In 2000, he aimed to improve ObGyn training by designing new forceps. The close collaboration that was started lead to the BirthSIM project: a partnership between Hospices Civils de Lyon and the Institut National des Sciences Appliquées. In 2002, he created the regional perinatal hotline that organize relations between 64 maternity units. He is now a Senior ObGyn at Lyon Sud University Hospital where he is developing a simulation center for midwifes and ObGyn.