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# AUTOMATION OF A MECHANICAL CHILDBIRTH SIMULATOR USING ELECTROPNEUMATIC COMPONENTS

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*This paper presents some new automatic procedures for a mechanical childbirth simulator BirthSIM. BirthSIM is a complete training system for simulating labor during childbirth. This simulator also tests new techniques for obstetric practice. BirthSIM consists of a dynamic pelvic model which simulates a pregnant human female and in which the newborn's head is located in the vaginal canal. The newborn's head is connected to a linear pneumatic actuator driven by two five-port proportional valves.*

*A global characterization of the static flow stage of the electropneumatic proportional valve Festo has been carried out. An analytical model has been obtained using characteristic 3D graphs where a set of curves gives the output mass flow rate as a function of the electrical input for different values of the pressure ratio (upstream/downstream). This model is useful for carrying out the synthesis of linear control laws for feedback control in position, velocity or force tracking according to the desired trajectories. The medical conditions are translated into an automation problem by the synthesis of input trajectories for the electropneumatic system. Position feedback control is necessary to position the head of the newborn on a horizontal axis. Also, position or force control is important in order to produce the movement of the head, the mother's natural contractions and the mother's pushing action.*

*In this study some control procedures has been proposed. Different childbirth cases can be simulated by the electropneumatic system. The validity of the proposed control method for simulating childbirth modes has been evaluated by means of experiments with an expert obstetrician.*

**Keywords:** BirthSIM simulator, Electropneumatic system, Childbirth procedures, Control algorithms

## 1 INTRODUCTION

Nowadays simulators have a real appeal in the medical environment. They enable doctors to visualize the position of the organs in the human body, to plan their movements and to carry out a more complete post operational control. In fact these simulations offer several advantages (safe training without any risks for the patients, saving of time and money, greater freedom for the operating theatre, etc). This training will be completed with experience learnt in the operating theatre. A birth simulator provides training and is a research tool for comparing various techniques in the use of obstetrical instruments (forceps and vacuum extractors) and to validate new techniques.

BirthSIM is a childbirth simulator developed in collaboration with INSA Lyon (Institut National des Sciences Appliquées) and HCL (Hospices Civils de Lyon) in France. BirthSIM is a dynamic functional simulator which takes into account the movement of a baby through its mother's pelvis. In fact this type of simulator will help to teach, in a realistic way, and in complete safety the medical techniques of childbirth in midwife schools and the Faculty of Medicine. It has been developed to enable obstetricians to learn how to perform the procedure for the first time.

Labor is described in three stages [5]. The first stage commences with the onset of labor and terminates when the cervix has reached full dilatation and is no longer palpable. The second stage or stage of expulsion begins at full cervical dilatation and ends with expulsion of the fetus. The third stage or placental stage begins with the delivery of the child and ends with the expulsion of the placenta. This study is especially concerned with the second stage. This generally lasts between thirty minutes and two hours. It is the phase during which the fetus goes through the cervix uteri and crosses the bony pelvis and then the soft pelvis to the vulva. During the second stage of a labor, the fetus is submitted to two types of phenomena. The first is uterine contractions

(UC), this is an involuntary activity of the mother generated by the uterine muscles. The UC can produce a uterine forces (UF). The second type of phenomena is maternal forces (MF), this is a voluntary activity of the mother solicited by a midwife or an obstetrician. So to complete the expulsion part of the labor the medical team must help the mother to synchronize her thrust with the uterine contractions during a normal birth. This concept is to overcome the resistance threshold necessary in order to expel her baby out of her uterus. In fact, the principle interest of choosing pneumatic components for the BirthSIM is to gain the ability to regulate the system stiffness easily for simulating these different efforts which occur in vivo cases. The position of the fetal head in pelvic canal is given by two parameters: station and location. The station of the fetal head is the distance of the head from the ischial spines as defined by the ACOG (American College of Obstetrics and Gynecology) [3]. This classification divides the pelvic canal into eleven stations from -5cm to +5cm every centimeter (see Fig. 1). The station +5cm corresponds to the instant where the fetal head is going to leave the vulva. The location concerns the rotation of the fetal head around the pelvic canal axis. Traditionally eight different locations (every 45°) are defined to describe the orientation of the fetal head orientation [3].

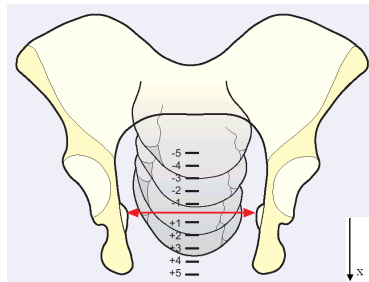


Fig. 1 Descent of the head is described relative to the ischial spines (ACOG classification [4])

This article is organized as follows: In section 2, involuntary efforts, voluntary efforts and the synchronization concept are described. In section 3, a description of BirthSIM simulator, simulation of uterine contractions and the mother’s efforts have been provided. Section 4 presents a control switching algorithm used for realizing the implanted birth procedures. Section 5 discusses the experimental results obtained for the static training mode and for the two dynamics training modes for childbirth procedures.

## 2 MATERNAL EFFORTS AND THE SYNCHRONIZATION CONCEPT

### 2.1 Involuntary efforts i.e. UC

Uterine contractions are due to the activity of muscles, essentially in the wall of the uterus. This contractile activity of the uterus makes it possible to push the fetus out [9]. It is a painful activity and can be identified by the mother who can feel it and by the obstetrician who can watch these UC on a tocography and can palpate them on the mother’s lower belly or feel the head advancing with each UC. Recording by internal tocography makes it possible to represent the intra-abdominal pressure variations as a function of time, as shown in Fig. 2. This curve, traced for ten minutes, can be described using several parameters. This characteristics vary from one mother to another [8].

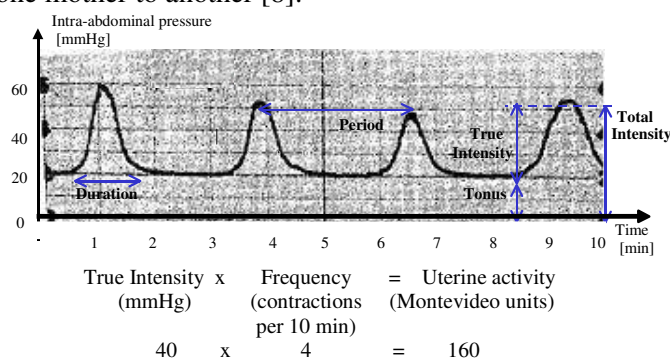


Fig. 2 Tracing the uterine contractions and their parameters [8].

## 2.2 Voluntary expulsive efforts

Maternal expulsive efforts are added to the phenomenon of the UC. These efforts from the mother press the uterus by raising the intra-abdominal pressure probably to 100 mmHg [5]. During a normal labor, there are generally 3 to 4 voluntary expulsive efforts per minute, each effort lasts between ten and thirty seconds as shown in Fig. 3. They can be provided by the mother when she pushes the baby at the moment when the obstetrician requires it, or by a midwife who applies an external effort using her hands on the mother's belly (not simulated in this study). This case occurs when the mother is tired and is unable to provide sufficient thrust.

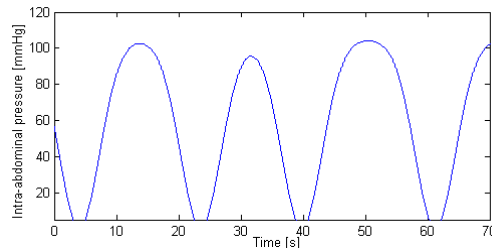


Fig. 3 Maternal expulsive efforts

## 2.3 Synchronization concept in a normal childbirth

During the second stage of labor the total expulsive efforts which enable the progression of the fetus are the MF and the UF. To overcome mechanical resistance, it is necessary to ensure that these two forces are quite synchronous (see Fig. 4(a)). If the total efforts are higher than the resistance threshold, progression of the baby inside the vagina occurs. This concept of resistance threshold is very difficult to quantify. It depends on the mechanical properties of the uterus and the vagina, these are defined by the resistance force exerted by the walls of the organs on the fetus. In this study the threshold is supposed constant at any moment but adjustable before each test. Fig. 4(a) shows very good synchronization, whereas Fig. 4(b) presents bad synchronization of the UF with the MF because the mother pushes too late.

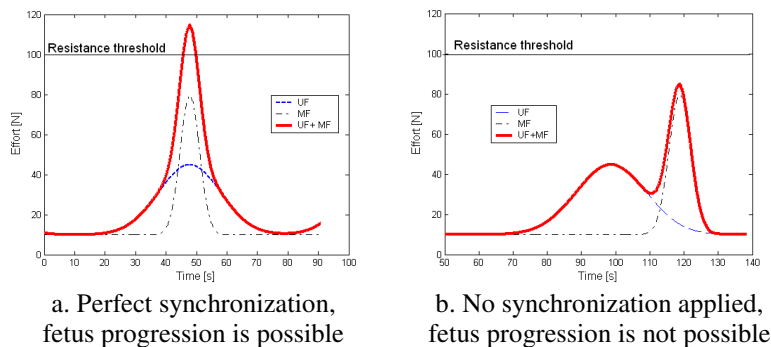


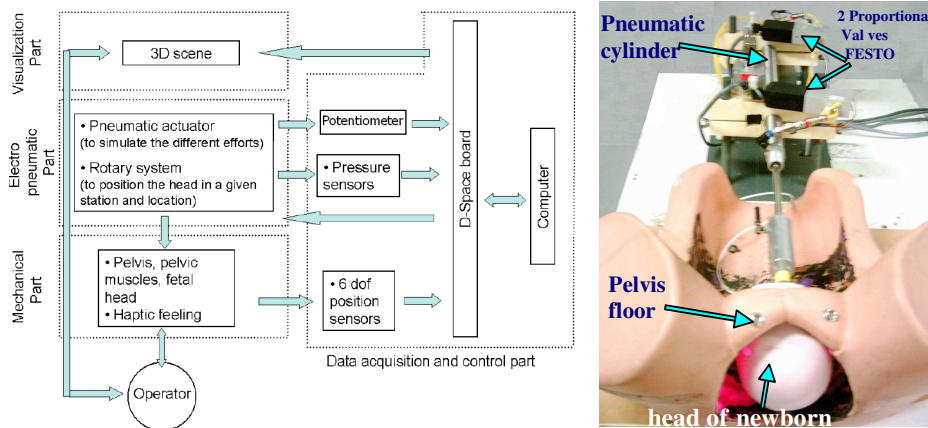
Fig. 4 Synchronization concept

## 3 BIRTHSIM SIMULATOR

In order to validate the new childbirth procedures developed, the BirthSIM simulator has been used [6],[7]. This consists of three parts: a mechanical part, an electropneumatic part and a visualization [6] as shown in Fig. 5(a).

The BirthSIM simulator mechanical part consists of anthropomorphic models of the maternal pelvis and the fetal head. This head has the main anatomical landmarks (fontanels, sutures, ears) and these enable a realistic examination [6]. The maternal pelvic model also has anatomical landmarks: ischial spines, pubis, coccyx and sacrum. With this simulator the medical team can feel the usual landmarks and can acquire haptic feeling as in a real delivery. They can make their diagnosis and the transvaginal assessment [1]. This diagnosis is to determine the position of the fetal head inside the pelvis to establish which procedures will be used for the delivery (vaginal delivery, Cesarean or instrumental delivery). The head is linked to a ball and socket joint and then to a linear pneumatic actuator. To allow the medical team greater interactivity with the BirthSIM

simulator, the operator also can observe in real time the different efforts carried out during labor in order to be able to ask the mother to push and for him to apply his tractive efforts when necessary.



a. Diagram of the three parts

b. Photograph of mechanical and pneumatic parts

Fig. 5 BirthSIM simulator

### 3.1 Pneumatic part of BirthSIM

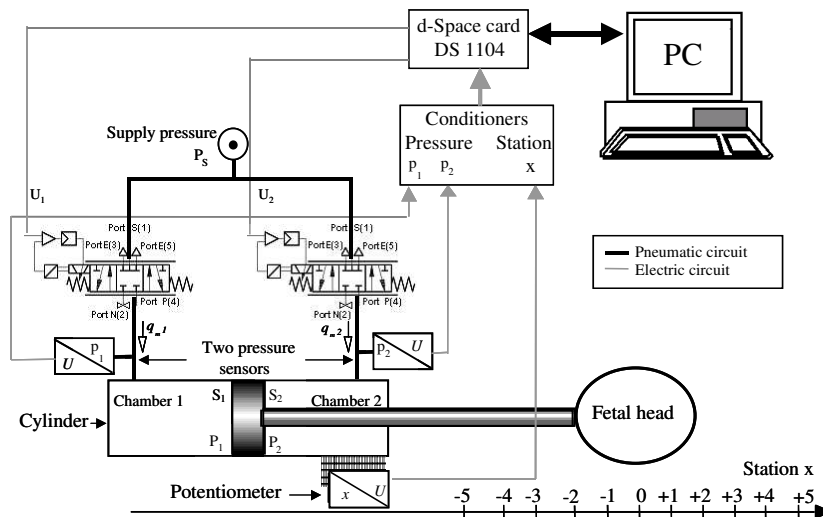


Fig. 6 Electropneumatic system of BirthSIM

The electropneumatic part uses two actuators which enable the user to choose a station and a location. A pneumatic actuator (respectively a DC motor) ensures the placement of the head at the desired station (respectively the location). In addition to its role of positioning the head, the pneumatic actuator also makes it possible to reproduce the various efforts presented in section 2.

Fig 6 shows an electropneumatic system chosen to reproduce ten different childbirth procedures. The system under consideration is an inline double acting electropneumatic servo-drive using a single rod controlled by two five-port proportional valves FESTO MPYE-5-M5-010B. A global characterization [12][13] of this electropneumatic proportional valve has been carried out to obtain an analytical model. The two proportional valves are controlled with opposite sign inputs [19] of ( $U_t$  and  $-U_t$ ), by adding a constant 5.041V [12], in the system under consideration for all the control algorithms. This system has three sensors as shown in Fig. 6. The head station  $x$  is given by an analog potentiometer and the two pressures  $P_1$  and  $P_2$  (in the two cylinder chambers) are given by two analog pressure sensors. The sensor data was run through a signal conditioning unit before being read by a dSpace acquisition board. The software Control Desk provided with a dSpace DS1104 controller board displays this digital data.

The electropneumatic system model can be obtained using three physical laws: the mass flow rate through a restriction, the pressure behavior in a chamber with variable volume and the fundamental mechanical equation. The pressure evolution law in a chamber with variable volume is obtained assuming the following assumptions [18]: air is a perfect gas and its kinetic energy is negligible. The pressure and the temperature are supposed to be homogeneous in each chamber. The process is polytropic and characterized by a coefficient  $k$ . Moreover, the electropneumatic system model is obtained by combining all the previous relations and assuming that the temperature variation is negligible with respect to average and equal to the supply temperature. The dynamics of the proportional valve may be neglected. So, the proportional valve model can be reduced to a static one described by two relationships  $q_{m1}(U_t, P_1)$  and  $q_{m2}(-U_t, P_2)$  between the mass flow rates  $q_{m1}$  and  $q_{m2}$ , the input voltages  $U_t$  and  $-U_t$ , and the output pressures  $P_1$  and  $P_2$ . The mechanical equation include pressure force, dry and viscous friction, and an external constant force due to atmospheric pressure. So the following equation gives the model of the system used:

$$\begin{cases} \frac{dx}{dt} = v \\ \frac{dv}{dt} = \frac{1}{M} \left[ S_1 P_1 - S_2 P_2 - b v - F_{dry} - F_{ext} \right] \\ \frac{dP_1}{dt} = \frac{k r T_s}{V_1(x)} \left[ q_{m1}(U_t, P_1) - \frac{S_1}{r T_s} P_1 v \right] \\ \frac{dP_2}{dt} = \frac{k r T_s}{V_2(x)} \left[ q_{m2}(-U_t, P_2) + \frac{S_2}{r T_s} P_2 v \right] \end{cases} \quad (1)$$

The main difficulty for model (Eq. 1) is to know the mass flow rates  $q_{m1}$  and  $q_{m2}$ . Fig. 7 shows (after having carried out a linear interpolation of the measurement points) the three-dimensional evolution of the mass flow rate as a function of valve-input control and its working pressure. An analytic model of the proportional valve is obtained from these static characteristics [12] and so a mathematical model for a static flow stage has been obtained from a polynomial approximation affine in control (Eq. 2):

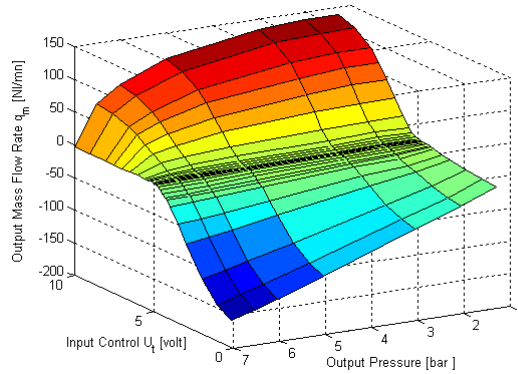


Fig. 7. 3D-global static characteristics

$$q_m(U_t, P_1) = \varphi(P_1) + \psi(P_1, \text{sgn}(U_t)) \times U_t \quad (2)$$

$\varphi(P_1)$  is a polynomial function whose evolution corresponds to the mass flow rate leakage from the port P (obtained for  $U_t = 0V$ ) (see Fig. 8(a)).  $\psi(P_1, \text{sgn}(U_t))$  is a polynomial function of the input control sign (see Fig. 8(b)) because it is different for the inlet ( $U_t > 0$ ) and for the exhaust ( $U_t < 0$ ). So from Eq. 1 and Eq. 2 the control mode of the electropneumatic system of BirthSIM can be obtained. This nonlinear model has been linearized around an equilibrium set. This is useful for scheduling the controller gains of the control algorithms which will be presented in the next section.

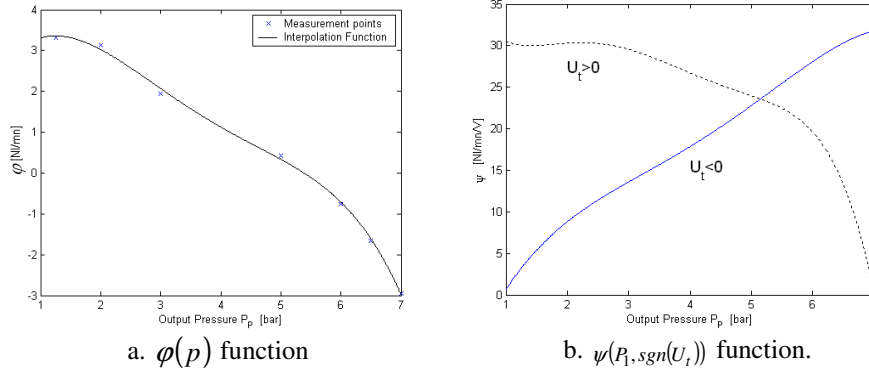


Fig. 8. Two polynomial functions of the analytical model of the proportional valve Festo [12]

### 3.2 Simulation of the uterine contractions and the mother's efforts

Today BirthSIM is able to simulate the MF and the UF. Fig.9 shows a graph simulating the UC, each contraction has been given by a Gaussian function as follows:

$$G(t) = \exp\left(-\frac{t^2}{d_{UC}}\right) \quad (3)$$

$d_{UC}$ : Duration of one contraction (see Fig. 9(a))

The UC simulated are described using four parameters with the aim of representing the real uterine contractions shown in Fig.2. Fig. 7(a) defines these four parameters with an important new one:  $d_{2stage}$  which represents a duration of a second stage of labor.  $d_{2stage}$  is an adjustable time lasting between ten minutes and two hours, it is a real time of labor allowing the fetal head to leave the pelvis entirely [9].

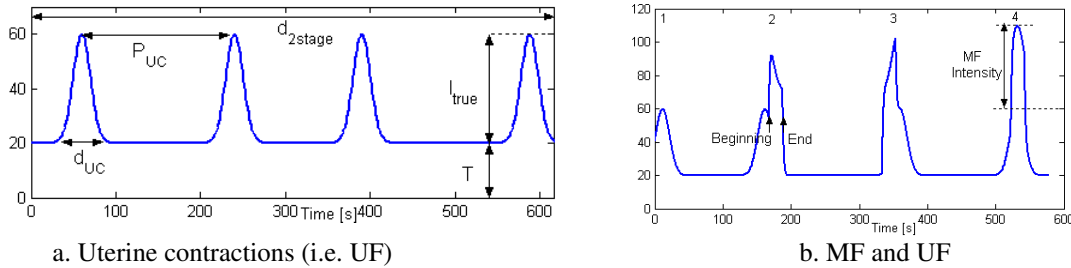


Fig. 9 Various maternal efforts simulated via BirthSIM in real time

Fig. 9(b) presents a series of the MF synchronized with the UF starting from the second UF. A threshold of mechanical resistance of 100 N is supposed, this shows that the synchronization is carried out starting from the third UF. This first synchronization is minimum and then it is more effective for the fourth UF. The instructor, who is an expert obstetrician, can control the MF by means of three adjustable parameters, he can choose, in real time, the beginning, the end and the intensity of each MF as shown in Fig. 9(b).

When considering the graph shown in Fig. 9 as the desired input trajectories for the electropneumatic system chosen for the BirthSIM simulator [6]. The medical conditions are translated into an automation problem. This makes it possible to automate the BirthSIM childbirth simulator.

## 4 CONTROL ALGORITHM

With the objective of implanting the two childbirth procedures presented in this paper, a switching control algorithm is used to control pressure force and velocity. The switching does not depend of an external signal, but is programmed online for desired tracking objectives. Reference [13] proposed a hybrid control methodology to switch between special objectives without damage to the process.

The force tracking control, shown in Fig.10, is required to produce the mother's natural contractions and the mother's pushing action. In fact, this tracking control enables the fetal head to be maintained in a position between two contractions in order to reproduce the resistive effort of the pelvic muscles which tends to prevent the baby advancing in the pelvic canal. The aim of this control algorithm is to be accurate in terms of

force tracking for the desired input trajectories which represents the MF and the UF shown in Fig. 9. The pressure force  $F_p$  is estimated from two pressure sensors as shown in Fig.10.

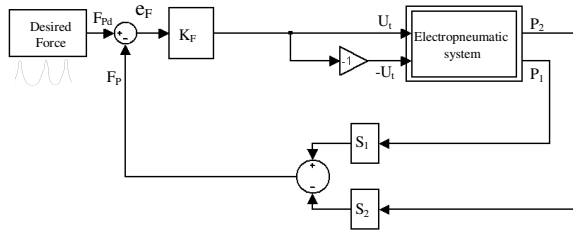


Fig.10 Force tracking

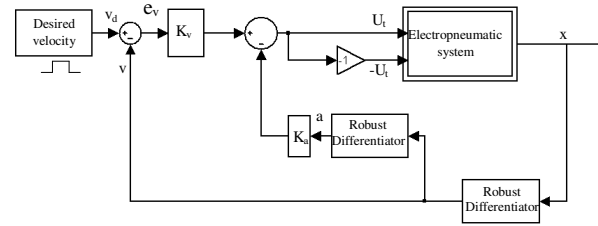


Fig. 11 Velocity regulation

The velocity regulation causes the baby's progression when the UF reaches its peak. In order to obtain a good response with this control algorithm, an acceleration feedback is carried out. A robust numerical differentiator, via the sliding mode technique proposed in [15], is used to obtain the velocity and the acceleration signals.

## 5 EXPERIMENTAL RESULTS

This paragraph first presents a static training mode, then two dynamic training modes for childbirth procedures realizable today as operating modes for the BirthSIM simulator.

### 5.1 Automatic installation of the fetal head in one station

This mode can be used to train the operator (midwife or junior obstetrician) to recognize a head station from sciatic spines by simple vaginal examination [10]. Another important use of this mode can also be to initialize the other modes. In fact, using a feedback control in position, BirthSIM is able automatically, on a request from the instructor, to position the fetal head in one of the eleven stations shown in Fig. 1.

The BirthSIM simulator is able, in the two modes presented, to reproduce the following scenario: the fetal head placed at a certain station (between 0 and +5), goes forward to the station +15, in a regular way, four times every 10 minutes, with an adjustable time lasting between 10 min and two hours.

### 5.2 Experimental simulation of the second stage of a normal labor

The aim of this mode is to simulate the second stage of a normal labor by supposing that the MF are absent e.g. the mother is tired and she cannot push well, or the operator has not asked the mother to push.

In this mode the head progresses because of the pressure efforts applied to the head. The graphic form of these efforts simulates the form of the uterine contractions shown in Fig.2.

To carry out this mode, the algorithm must firstly be initialized, and then the force tracking control algorithm shown in Fig. 10 can be applied. For the initialization the instructor must choose the initial position (among the eleven possible stations) via the first mode, define the amplitude of the movement  $x_{leave}$  with which labor can be simulated (between +15 and +20) and define the velocity progression of the head during this stage of labor. Then to start this mode, the instructor presses on a button which causes the execution of the following algorithm:

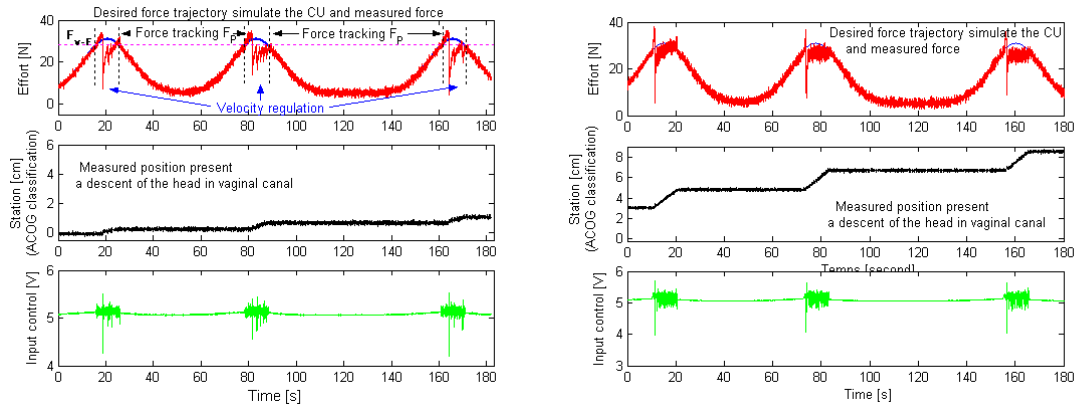
- |  |   |
|--|---|
| 1. $x_d \leftarrow [-5, +15]$ ;<br>$v_d \leftarrow [\text{value defined}]$ | Position and velocity desired defined by the instructor   |
| 2. $F_{v\_F} \leftarrow [\text{value defined}]$                            | Condition defined by the instructor, ensuring the switching and thus the slow displacement of the head. It is important to choose this value lower than the dry friction of the electropneumatic system of BirthSIM otherwise the head could be expelled quickly. |
| 3. $x_{leave} \leftarrow [+15, +20]$                                       | Station for which the new-born leaves the pelvis completely.  |
| 4. <b>while</b> $x_{rt} < x_{leave}$ <b>do</b>                             | If the position, measured in real time via the sensor position, is lower than $x_{leave}$ the second stage of labor can be simulated.   |
| 5. <b>if</b> $F_{Pd} \geq F_{v\_F}$  | Desired pressure force applied to the head  |
| 6. $Cl_v \leftarrow 1$ ; $Cl_F \leftarrow 0$                               | Switching from force tracking control to a velocity regulation  |
| 7. <b>endif</b>  |   |
| 8. $Cl_v \leftarrow 0$ ; $Cl_F \leftarrow 1$                               | Opposite case of stage 6, so the head can be maintained in a new position.  |



### 9. endwhile

10.  $U_1 \leftarrow [4 \text{ V}], U_2 \leftarrow [3.5 \text{ V}]$  Arriving at station  $x_{\text{leave}}$  allows the control algorithm to be stopped and to apply 4V and 3.5V respectively to the inputs controls  $U_1$  and  $U_2$ . These values enable a progressive displacement of the head [12] starting from a position  $x_{\text{leave}}$ . This makes the operator able to leave the head without pneumatic resistance. In fact, on the pressure gain characteristic of the proportional valve [12], the input controls 4V and 3.5V correspond to two different pressures providing a positive effort  $F_P$  which ensures the forward progression of the head. With input controls  $U_1 = U_2 = 0\text{V}$  great acceleration can be obtained.

### Experimental simulation of the UC during the expulsion stage of a normal labor



a. A 2<sup>nd</sup> stage can last 56min with  $v_d = 0.075 \text{ cm/s}$

b. A 2<sup>nd</sup> stage can last 21min with  $v_d = 0.2 \text{ cm/s}$

Fig. 12 Experimental simulation for only 3min of a second stage of normal labor in switching between force tracking and velocity regulation controls

Fig. 12(a) shows the response of the pneumatic system to the two desired input signals, force tracking and velocity regulation controls applied to the fetal head. The form of input force trajectory simulates the UC (see Fig. 2). The system's response is accurate in terms of force tracking except in the time intervals when the head advances, under an application of velocity regulation control. In the example of Fig. 12(a), the effort trajectory is applied to the head placed at station 0. The head advances for each arrival of uterine contraction. The amplitude of displacement depends on the  $F_{v,F}$  and  $v_d$ :

- For a constant value of  $v_d$ , the more  $F_{v,F}$  is weak, the more the displacement of the head starts early and finishes late and so the progression has more amplitude.
- For a constant value of  $F_{v,F}$ , the greater the value of  $v_d$ , the greater the amplitude of displacement.

The choice of  $F_{v,F}$  is difficult because the  $F_{\text{dry}}$  is related to many parameters (position, pressure, temperature, air quality, etc). For the results presented the dry friction was about 32N so the threshold  $F_{v,F}$  was fixed at 28N.

Fig. 12(a) shows a progression of the head equal to 0.4cm for each arrival of the UC with a desired input velocity equal to 0.075 cm/s. In this case, the second stage of labor can last about one hours ( $d_{2\text{stage}} = 56\text{min}$ , see Fig. 9). Fig. 12(b) shows a displacement of two stations during the peak of the UC for a desired velocity equal to 0.2cm/s so, in this case, the second stage lasts 21min.

Fig. 12 shows, for each example, an input control applied to one of two proportional valves, the other one being of the opposite sign. It is important to note that there is no saturation of the input control of the system.

### 5.3 Experimental simulation of second stage of normal labor by applying the synchronization concept

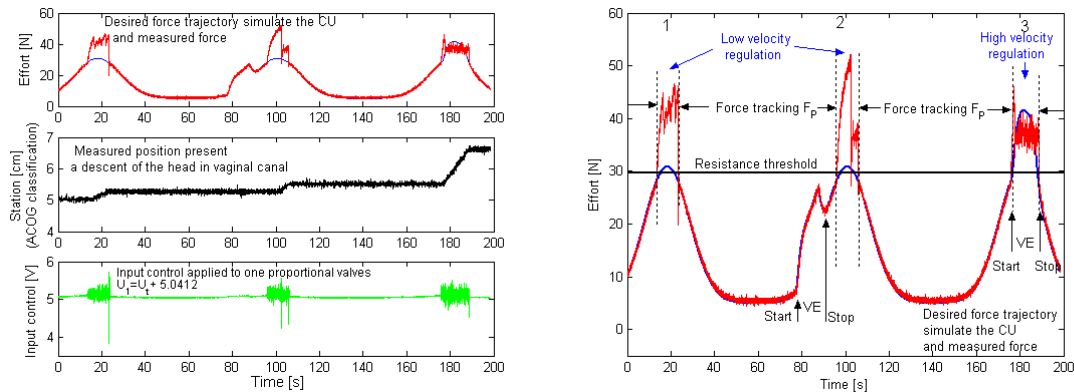
In addition of the aim of this mode to simulate the second stage of a normal labor, it also used to train the midwife or the junior obstetrician to synchronize the MF with the UF. In fact, this mode supposes that the voluntary expulsive efforts generated by the mother can be applied for the last 20 minutes (if the labor lasts 2 hours) and during the last 2 minutes (if the labor lasts 10 minutes). So, from +3, +4 or +5cm, the instructor can press one button on the graphic interface at the moment when the operator asks the mother to push. This

can address, to the BirthSIM, a signal that adds a complementary progression to the fetal head. This displacement is immediate, it lasts from 10 to 30 seconds with three level of amplitude: short (1 cm), medium (3 cm) and long (7 cm). This displacement must be synchronized with the UF produced. The form of the desired input trajectory applied to the fetal head can not simulate only the UF but also the MF.

To carry out this mode, the algorithm must firstly be initialized so the instructor must determine, in addition to  $x_d$  and  $x_{leave}$ , two velocities ( $v_{d-low}$  and  $v_{d-high}$ ) for the head progression. Then the force tracking control algorithm shown in Fig.10 can be applied.

When the pressure effort  $F_p$  reaches the  $F_{V\_F}$ , a new algorithm makes it possible automatically to switch between a force tracking control and a velocity regulation control. This new algorithm is the same as the previous one except that stage 6 has been modified. This stage 6 makes it possible automatically to select a force tracking control,

- or high velocity regulation control ( $v_{d-high} = 0.11$  cm/s) if the synchronization of MF and UF is respected,
- or low velocity regulation ( $v_{d-low} = 0.06$  cm/s) if this synchronization is not applied very well.



a: System response. Corresponding head progression. Input control applied to the proportional valve. b: Enlargement of the pneumatic system response.

Fig. 13 Realization of a second stage of normal labor (when the woman can push) in switching between force tracking and velocity regulation controls at two velocities ( $v_{d-low} = 0.06$  cm/s,  $v_{d-high} = 0.11$  cm/s)

Fig. 13 shows the response of the pneumatic system to a desired input force trajectory, by adding in real time, near of the second and third peaks of the UC, an additional signal which simulates the MF. The operator must feel a change in the resisting effort due to the UC and therefore ask the woman to push for each arrival of the UC. From the second UC shown in Fig.13 the operator tried to carry out the synchronization by asking the mother to push but he did not choose the right moment because he asked the mother to push too early, or the woman did not respect the operator's request. On the other hand, for the third UC, the operator carried out the synchronization very well.

The system's response is accurate in terms of force tracking except in the time intervals when the head advances under an application of velocity regulation control. In the example of Fig. 13 the effort trajectory is applied to the head placed at station +5. The head advances 0.25 cm for both the first and the second UC, and then 1.2 cm for the third contraction. The amplitude of displacement depends on the  $F_{V\_F}$  and the two desired input velocities  $v_{d-low}$  and  $v_{d-high}$ . Fig. 13 also shows input control applied to one of the two proportional valves, the other one being of the opposite sign.

## 6 CONCLUSION

This paper presents the development of a childbirth simulator whose characteristics correspond to the needs of obstetricians [20]. The two childbirth procedures implanted make BirthSIM an active and dynamic simulator. The instrumentation used can transmit in real time the following information to the operator:

- station, progression and velocity of the head and possibly its acceleration;
- the form of the pressure effort trajectories developed by the pneumatic actuator;

The operators can use this information to learn how to achieve the synchronization necessary between different efforts produced during labor with maximum safety.

Currently several features of the BirthSIM simulator are under development and validation. The first point relates to the pneumatic actuator which reproduces the different efforts on the fetal head. Two directions of research are currently in hand. Firstly, the synthesis of nonlinear control laws of the electropneumatic system for implanting other childbirth cases, for example instrumental delivery using obstetrical forceps or a vacuum extractor, and secondly the development of an interface allowing the simulation of the pelvic muscles. The second point is for training operators in a reference instrumental delivery with 3D visualization interface and on the comparison of the repeatability of the synchronization between novice obstetricians and expert obstetricians.

## 7 LIST OF NOTATIONS

Cl	Closed loop control		P	Pressure	Pa
$\phi(.)$	Polynomial leakage function	kg/s	$q_m$	Mass flow rate provided from the proportional valve	kg/s
$\psi(.)$	Polynomial function	kg/s/V	r	Perfect gas constant related to unit mass	J/kg/K
a	Acceleration	m/s <sup>2</sup>	S	Piston area	m <sup>2</sup>
b	Viscous friction coefficient	N/m/s	T	Temperature	K
e	Erreur		t	Time	S
F	Force	N	U	Proportional valve input control	V
$G(.)$	Gaussian function		$U_t$	Translation of U, ( $U_t = U_1 - 5.041$ ), ( $-U_t = U_2 - 5.041$ )	V
k	Polytropic constant		V	Volume	m <sup>3</sup>
K	Controller gain		v	Velocity	cm/s
M	Total moving load mass	kg	x	Position	cm

### Subscript

d	Desired	p	Pressure
dry	Dry friction	rt	Real time
E	Exhaust	S	Supply
ext	External	$v_F$	Switching between force tracking and velocity regulation controls
F	Force	x, v	Position, velocity
d-high	Desired high velocity	1	Chamber 1 of cylinder
leave	New-born leaves the pelvis completely	2	Chamber 2 of cylinder
d-low	Desired low velocity		

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