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# A Magnetic Transducer for the Detection of the Fetal Engagement Level in Part-Task Trainers

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**ABSTRACT** Assessing the level of descent of the fetal head in the birth canal during a pelvic examination is a critical skill required by gynecologists and midwifes to avoid injuries for the mother and the newborn. A way to train this ability in a riskless environment is through medical simulation; however, the majority of tools do neither provide visual feedback of the location of the fetus inside the birth canal, nor give the possibility to quantitatively assess this skill. This work aimed at creating a low-cost transducer based on magnetic fields that discriminates between nine levels of descent of the fetal head, namely engagement levels, usable with part-tasks pelvic trainers. Starting with neodymium magnets, we designed a magnetic transducer so that each level was identified by a unique combination of magnetic fields. Three Hall effect sensors detect polarity and intensity of the field generated by 27 permanent magnets, organized in a $9 \times 3$ matrix, and each level, corresponding to one row of the matrix, is uniquely encoded by the sensors. The system was theoretically analyzed in simulation, then tested using a customized prototype and finally integrated into an existing birth simulator. The transducer is wireless and avoids any obstruction in the birth canal, as it does not require any power supply to generate magnetic fields and the sensors are connected to the hardware in the fetal manikin. Also, its dimension and ease to install make it usable with many pelvic models, which can be turned into sensorized simulators providing visual feedback and quantitative evaluations.

**INDEX TERMS** Fetal position, Hall effect sensors, magnetic transducer, medical simulation, obstetrics and gynecology, neodymium magnets, permanent magnet sensors.

## I. INTRODUCTION

Medical simulation is essential for physicians, nurses and more generally for healthcare workers. In fact, simulation has been widely used for training, skill rehearsals and performance evaluation, showing improved training outcomes [1]–[4]. In gynecology and obstetrics, simulation is used to train several skills: breast and pelvic examinations, endoscopy, minimal invasive surgery, deliveries, medical emergencies, ultrasound training and communication ability [5], [6]. Indeed, obstetrics is a field characterized by high-risk situations, requiring mastery of several skills [6]. Among the most important tasks a student needs to learn, there is pelvic examination during labor. Such skill is critical to correctly estimate the fetal position in the birth canal, to avoid possible injuries to the mother or the fetus [6]. This is particularly difficult for novice, as they need to manually recognize whether the fetal head is above or below the narrowest diameter of the birth canal, discriminating between different engagement levels one centimeter apart [7].

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To train this ability several simulators are available, spanning from low-fidelity, simple yet reliable pelvic models, to high-fidelity systems with embedded sensors and actuators [8]. Although high-fidelity systems permit a realistic simulation of labor and a monitoring of the learner's performance, low-fidelity part-task trainers are largely preferred for several reasons. First of all, high-fidelity simulators are expensive tools requiring dedicated technicians and a permanent setup [6]. Furthermore, they have automatic birthing mechanisms that may not fit with the specific learning goals of the instructor [6]. Finally, theories on fidelity and educational outcome suggest that high-fidelity may be beneficial for advanced learners, while novices should be trained on low-fidelity systems to reduce their cognitive load [6], [9]–[11]. Hence, low-fidelity systems may be a better option for health professionals who rarely perform obstetrical tasks and need to know only basic skills [6], [12]. Part-task trainers have the advantage of being small, low-cost and easy to use and maintain [6]. Further, they are usable in several contexts other than simulation centers (i.e. rural areas, hospitals) [6], [13]. However, one of the biggest disadvantages of low-fidelity models available for pelvis examination during labor is that they are very simple tools without sensors. This limitation does not allow measure of performance or provide on-line and off-line feedback. Therefore, the lack of sensors decreases the power of these simulators as instruments for self-practice and for evaluation of trainees' skills. In fact, feedback and quantitative assessment of learner's skills are fundamental when students learn how to perform a pelvic examination. Specifically, for testing the ability to correctly evaluate the engagement level of the fetal head in the birth canal with part-task trainers, the response of the learner is compared with those of the instructor. However, a study performed using a birth simulator revealed that examiners misjudged the station a third of the time [14] making errors greater than 1 cm.

To fill this gap, we developed a device which tracks the engagement level in low-fidelity models. In particular, we were interested in designing a tool that could turn a low-fidelity system into a sensorized simulator, able to assess students' ability and provide visual feedback on their performance.

From an engineering perspective, the fetal head can be considered as a body having a specific position inside the birth canal. Several sensors can detect the position of a body with millimeter resolution; among them there are ultrasound, optical, capacitive, inductive and magnetic systems. Systems based on ultrasound allow the detection of an object without being affected by its color or light conditions. However, they have the disadvantage of being limited by artifacts due to the return echoes deriving from objects near the target and also by soft materials [15]. Similarly, capacitive and inductive systems are disturbed by objects in the vicinity of the sensor [15]. Optical sensors detect objects (hard or soft), but have the defect of being influenced by environmental conditions [15]. Also, active systems require two powered devices: transmitter and receiver, while passive ones cannot discriminate between nearby objects [15]. All these requirements may be problematic in the context of birth simulation. For our purpose we used Hall effect magnetic sensors coupled with neodymium magnets. In fact, this technology uses permanent magnets to generate magnetic fields, without requiring any electrical connections other than those powering the sensors. Further, these sensors are neither altered by environmental conditions, excluding external magnetic fields, nor by the presence of non-magnetic objects close to the magnets.

While designing the magnetic transducer to measure the engagement level, our main goal was to implement a small, easy to install/use, and low-cost system compliant with low-fidelity simulators. An additional important requirement was to have sensors located on the fetal manikin, thus keeping the system wireless and the birth canal clear from any hardware or electrical connection.

In this work, we present how this system was firstly simulated, then tested on a custom-made setup, demonstrating the ability to detect different engagement levels, one centimeter apart. Ultimately, the system was installed into eBSim, a low-cost birth simulator prototype designed in our laboratory, enabling this simulator to provide reliable real time feedback and on-line evaluation of users' ability in performing pelvic examinations during labor.

The magnetic transducer we designed can be integrated in existing part-task trainers, turning them into sensorized simulators for the training and evaluation of obstetric skills. In other words, such a system could answer the need for a portable, efficient and affordable solution, easy to install and use, that would allow a large population of professionals and students to train and improve their ability in estimating the engagement level of the fetus in the birth canal. This would help to reduce the risk of wrong evaluations, ultimately resulting in better outcomes during the birth process.

## II. BACKGROUND: THE CLINICAL PROBLEM OF CORRECTLY ESTIMATING THE FETAL ENGAGEMENT LEVEL

The birth canal is characterized by the ischial spines (Fig. 1), which are halfway between the pelvic inlet and the outlet [7]. They are of great obstetrical importance, as their distance limits the narrowest diameter of the pelvic cavity [7]. The American College of Obstetrician and Gynecologists (ACOG) divides the pelvis into eleven stations. Each station corresponds to a centimeter above or below the ischial spines [7], [14]. During cephalic deliveries, the head descends from the inlet (level $-5$) toward the ischial spines (level 0; Fig.1). Once the biggest diameter of the fetal head has passed the ischial spines, the head is defined as "engaged" and the fetus keeps descending passing stations $+1$ to $+5$ [7]. Stations $-5$ and $+5$ are easy to guess: when the fetus is at station $+5$, his head is physically visible; conversely, station $-5$ corresponds to a situation in which the head is not detectable during pelvic examination. The 9 stations in between are difficult to discriminate, thus training and experience are needed to acquire the ability to precisely recognize them. This skill is fundamental for avoiding risky situations during labor and for planning operative deliveries [6], [14].

## III. MAGNETIC TRANSDUCER DESIGN

### A. HARDWARE

The system we designed consisted of two parts:

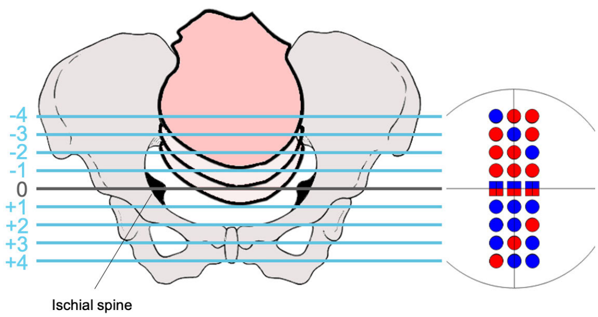


**FIGURE 1.** Correspondence between levels of engagement and magnetic transducer configurations. Left: engagement levels of the fetal head in the birth canal. They are equally spaced and range from −40 mm to +40 mm with respect to the maternal ischial spines (level 0). Right: model of the magnetic matrix; each circle is a magnet oriented such that north poles are in red, and south poles in blue.

- A 9 × 3 matrix of 27 cylindrical neodymium magnets (axial magnetization, radius 4mm, height 8mm; Fig. 1, Fig 2). The nine rows of the matrix correspond to the nine engagement levels (Fig. 1), i.e. the three magnets of each row generate magnetic fields that uniquely identify each level.

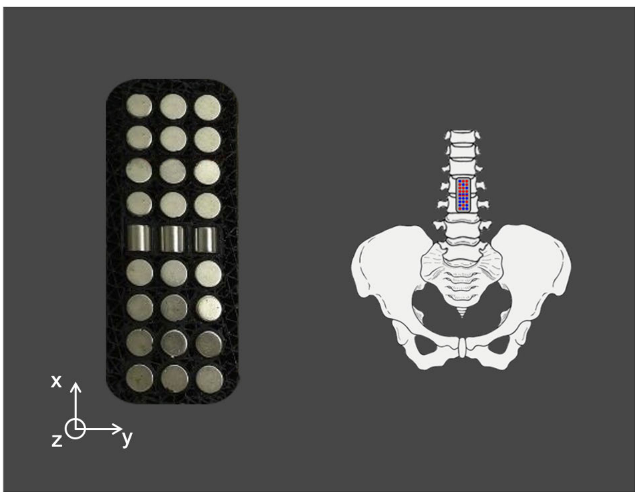


**FIGURE 2.** Magnetic matrix. Left: custom-made 3D printed PLA framework fitting nine rows of three neodymium magnets each. Each row encodes an engagement level. Three magnets coding level "0" (in the middle of the framework) are perpendicular to the main matrix. The dimensions of the framework are 100 × 40 × 7 mm. Right: Positioning of the magnetic matrix in the physical part of the birth simulator eBSim. The device is located outside the birth canal, 205 mm above the ischial spines (level 0).

- A bar with three Hall effect magnetic sensors (Si7211, Silicon Labs, USA) aligned as the three magnets, measuring the magnetic flux density generated.

The magnetization axis of all the magnets, but the three in the central row, had the same direction, perpendicular to the surface of the matrix. These magnets had equal or opposite polarity, i.e. equal or opposite positions of their south (S) or north (N) poles (Fig. 1). The position of the south and the north poles of three magnets in each row was selected to uniquely code each engagement level within the ranges [−4, −1] and [+1, +4] (Fig, 1; Fig 3; Table 1).

**TABLE 1.** Configuration of the magnetic matrix. Every engagement level is associated with a combination of three polarities detected by the Hall effect sensors. "N" indicates north poles, "S" south poles.

| Level | Magnet 1 | Magnet 2 | Magnet 3 |
|---|---|---|---|
| -4 | S | N | N |
| -3 | N | S | N |
| -2 | N | N | S |
| -1 | N | N | N |
| 0 | / | / | / |
| +1 | S | S | S |
| +2 | S | S | N |
| +3 | S | N | S |
| +4 | N | S | S |

To identify the engagement level 0 we created a region where the magnetic flux density was negligible and interpretable as 'no field' by rotating three magnets of 90 degrees (Fig. 3). With this configuration, the north poles are attracted to the nearby south poles and above these magnets of the central row there is a region of almost null magnetic flux density (i.e. below the threshold for detecting the field; Fig. 3).

Notice that each sensor detects the intensity of the overall magnetic flux density generated by all the nearby magnets and, as explained in detail in the following simulation section, this prevents the detection of spurious transitions (Fig. 3, Table 2).

All the magnets are positioned in a custom-made support, allowing a precise and fixed location. The support was designed on Autodesk Fusion360 (Autodesk, USA), and 3D printed (Delta WASP 2040, WASP, Italy), resulting in a Polylactic Acid (PLA) bar. The bar is 100 mm long, 40 mm wide and 7 mm high, with 27 holes fitting the magnets; the distance between the centers of the two adjacent holes (raw or column) is 10 mm (Fig. 2).

The magnetic matrix itself does not need any electrical connection to generate fields, as the magnets are permanent. Such fields can be detected by three Hall effect magnetic sensors, small and inexpensive sensors that require minimal power supply. For our purpose, we connected the sensors to a microcontroller: according to a supply voltage of 3.3 V, the output value of the magnetic sensors varies between 0 and 3.3 V, operating at a magnetic flux density value of −20.47 mT and +20.47 mT. Since we used Arduino UNO, the sampled signal was converted using 10 bits corresponding to a value equal to 0 for −20.47 mT and a value of 675 to 20.47 mT, with 0 T being in the middle of the range.

### *B. SIMULATION*

The 3D simulation was run on the commercial Finite Element Method software COMSOL Multiphysics® version 5.3a (COMSOL inc., Stockholm, Sweden), the Magnetic Fields no Current module (i.e. induced currents are neglected in the simulation) was used to solve the magnetostatic Maxwell equations. To simulate the magnetic flux density distribution,

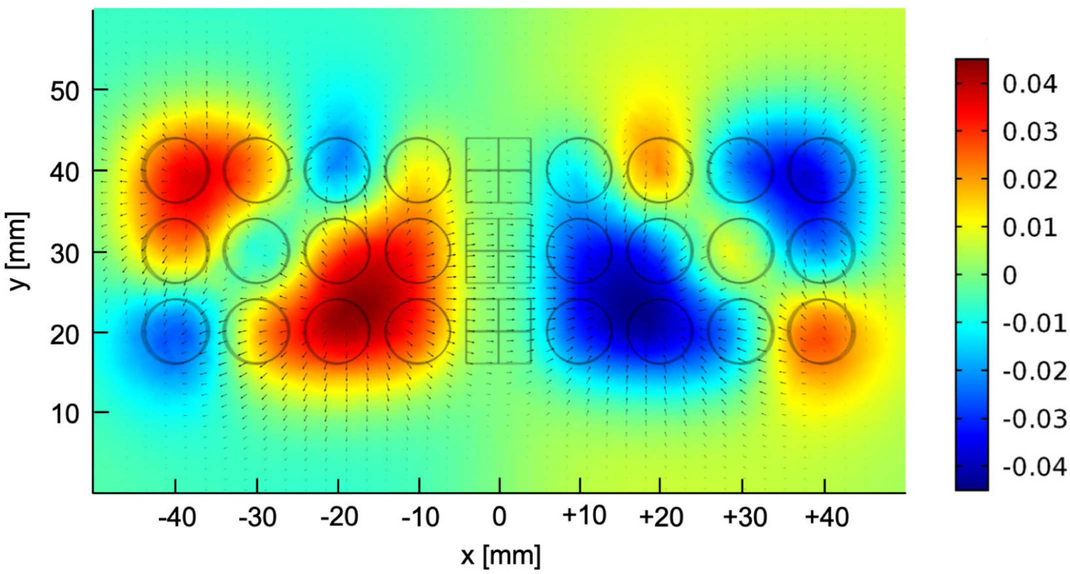


**FIGURE 3.** Results of the COMSOL simulation, top view. Colorbar shows the z-component of the magnetic flux density (T) at a distance of 10 mm over the 27 magnets.

**TABLE 2.** Results of the COMSOL simulation. Values of the z component of the magnetic flux density recorded, expressed in mT, at a distance equal to 10 mm from the magnets for each position. Columns represent the levels of engagement while rows indicate the magnets.

| | Engagement Level | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | -4 | -3 | -2 | -1 | 0 | +1 | +2 | +3 | +4 |
| (mT) | 36.11 | 18.16 | -18.49 | 12.55 | -0.01 | -12.97 | 18.36 | -18.91 | -36.96 |
| | 21.10 | -7.33 | 26.14 | 29.34 | 0.07 | -29.45 | -26.19 | 8.74 | -21.72 |
| | -24.69 | 19.99 | 42.08 | 29.11 | -0.03 | -29.09 | -43.43 | -21.11 | 23.90 |

we firstly set a magnetically isolated box region of 128 mm $\times$ 68 mm $\times$ 48 mm of the space limiting the area of the simulation. We selected these limits because we aimed to analyze how the magnets interact with each other in a space equal to the simulated birth canal, that is located over the matrix. Indeed, we set a simulation box which is slightly bigger than the matrix in the x- and y- dimensions and almost seven times bigger along the z-axis. Then, we added 27 cylindrical magnets complying with the flux conservation principle and having magnetic properties of neodymium: axial magnetization, radius 4 mm, height 8 mm; magnetic remanence 1.35 T. The magnets were organized into a 9 $\times$ 3 matrix with a distance between the centers of two nearby magnets of 10 mm, following the positioning and orientations of the magnetic matrix we designed (Fig. 1, Fig. 2).

Subsequently, we ran the simulation to analyze the distribution of the magnetic fields on a volume 95 mm $\times$ 26 mm $\times$ 17 mm with a mesh size of 0.1 mm, verifying that every single engagement level would be uniquely identified. Specifically, we considered Hall sensors operating between $-20.47$ mT and $+20.47$ mT and magnets with 1.35 T magnetic remanence, as the ones we selected. Considering the characteristics of the Arduino analog to digital converter and the magnetic noise of the sensors, we set 0.1 mT as threshold for detecting the presence of magnetic flux density as well as for detecting difference between two levels of its intensity.

Firstly, we measured how movements along the z-axis, i.e. the axis perpendicular to the matrix of magnets, influenced the magnetic flux. This check was performed to verify that for each point of the volume of interest, i.e. in the birth canal, the magnetic flux was clearly detectable. We found that the optimal sensor-matrix distance ranged between 8.8 and 15.4 mm. At distances smaller than 8.8 mm the z component of the magnetic flux density is always greater than $\pm 20.47$ mT, and the sensors reach their operating limits. In particular, distances between 0 and 8.8 mm allows detecting all the configurations/stations based on the magnet polarities, but without the possibility to control for spurious transitions, as the sensors can only detect whether the field below them is positive or negative. On the other side, a sensor-magnet distance greater than 15.4 mm does not guarantee that the sensors can clearly discriminate uniquely different positions. This working range suits our initial goal to design a system usable with pelvic simulators, having the sensors on the fetal manikin and the magnets on the pelvis. Indeed, a distance greater than 15.4 mm is unlikely in the birth canal, considering its physical dimensions. Similarly, 8.8 mm is feasible as a lower limit, considering the soft materials covering the system simulating the tissues of the pelvis.

Considering the above-mentioned z-axis limits, we verified the effects of translations along the y-axis, i.e. axis parallel to lines connecting the center of three magnets on a same row (Fig. 2). Results indicate that the system can tolerate lateral translations of the Hall sensors in the range ±4 mm with respect to the center of the underneath magnet. This range fits our purpose, because the sensors' bar will be placed on the body of the fetal manikin, allowing negligible translations in the y-axis (<±4 mm) due to the diameter of the birth canal.

After setting the z and y working limits, we analyzed the translations along the x-axis, to verify the absence of spurious transitions in the sampled volume of interest. However, given that the purpose of the measurement is to identify local field polarity rather than the exact values, to uniquely codify 9 levels 10 mm apart; an accuracy greater of 0.1 mm is not required for our system. Moreover, the field detectable between two tested points (as defined by the selected mesh) is an intermediate value with respect to its extremes. Thus, spurious transitions are always avoided as the magnetic flux is unique in all the ranges we analyzed. In other words, similar values can be detected only in nearby points.

Finally, we focused on level 0, corresponding to the central line of the matrix. In particular, we wanted to confirm that the magnetic flux over that area was negligible between 8.8 and 15.4 mm in the z-axis. As expected, the z component of the magnetic flux density ranges from −3.6 mT to 3.6 mT; these values are lower with respect to those detected in other levels. This is due to the fact that a north pole is attracted to the south magnetic pole in close proximity, resulting in an area where the magnetic flux is sufficiently low to be considered as zero. Fig. 3 and Table 2 show the results of the simulation when the sensors are centered with respect to the main matrix and the sensor-magnet distance is 10 mm.

We did not test for rotation (and thus to roto-translation) of the bar with the three Hall sensors with respect to the matrix because the sensors' bar will be firmly fixed in the fetal manikin body over an area which would translate in the pelvis without rotations, due to the spatial constraints of the birth canal.

### C. TEST

The simulation of the system was followed by an empirical test, aimed at assessing whether the physical system would work in the part-task trainer simulator available in our lab, as predicted by the simulation. Specifically, we verified whether the system allow the identification of nine engagement levels 10 mm apart (Fig. 1) with a precision compatible at least with that required in the clinical practice: during a delivery, the midwife has to manually estimate the level of the birth canal where the largest diameter of the fetal head is passing through. From the obstetrical perspective the midwives are required to classify the heads' position according to 9 levels one cm apart (Fig. 1).

To do so we compared the readings of the new magnetic transducer with those obtained by a linear potentiometer (BOURNS PTB0143-2010BPB103; 100 mm). Since the spatial constraints of a maternal pelvis would not support simultaneous measures of the two systems (i.e. transducer and potentiometer), we built a setup specifically designed to test our system.

In the custom-made setup we secured the matrix of permanent magnets to a wood platform (310 × 310 mm) where a bar mounting the three Hall sensors could linearly translate on two aluminum tracks, aligned with the longer sides of the matrix (Fig. 4). Thus, the bar could slide parallel to the matrix of magnets, with a fixed magnet/sensor distance of 10 mm along the z-axis, detecting the magnetic fields below it (Fig. 4). We decided to verify the system to 10 mm distance along the z-axis, since this would be the maximum allowable distance (worst case scenario) in the part-task trainer simulator which will be equipped with the magnetic transducer, considering the birth canal diameter and the distance between the fetus and the pelvis.

The potentiometer measured the position of the bar that detected the magnetic fields generated by the matrix (Fig. 4; see also hardware and simulation sections). Both the potentiometer and the magnetic sensors of the transducer were connected to an Arduino UNO board. The magnet matrix was positioned such that its level 0 corresponds to the middle range of the potentiometer. From the simulation, we extracted the values of the magnetic flux in 9 points, 10 mm apart, theoretically corresponding to the engagement levels. Namely, for each of these 9 levels we extracted the three values of magnetic flux we expected the hall sensor to read at a distance of 10 mm along the z-axis. Starting from these values, we set for each sensors' measure, a range of variation equal to ±4 mT with respect to the simulation values. Then, we verified whether and to what extent in the real system these values uniquely corresponded to the 9 positions 10 mm apart. Within this framework, if the head's diameter is ideally located 24 mm above the ischial spines, our system would classify that position as −2. If the trainees would locate it in position −2 this would be considered correct, while −1 or −3 the clinical evaluation would be considered acceptable.

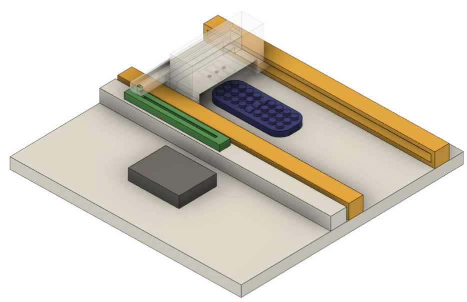

**FIGURE 4.** Experimental Setup. Two tracks (yellow) allow the translation of three Hall effect magnetic sensors (red) located 10 mm above the magnetic matrix (blue). A linear slide potentiometer (green) measures the translation of the sensors which, in turn, detect the level of engagement defined by a combination of three magnetic fields. An Arduino UNO board (grey) collects data from the setup.

Specifically, we performed 60 translations, moving the sensors' bar over the magnetic matrix back and forth (30 translations from level −4 to level +4 and 30 from +4 to −4; Fig. 4). During each transition, we recorded the

**TABLE 3. Performance of the magnetic transducer. Mean, Standard Deviation, Minimum and Maximum value and range of measurement recorded by the potentiometer over 60 repetitions. Mean and Maximum Deviation from the expected value. Columns indicate the nine levels of the magnetic transducer.**

| | Engagement Level | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (mm) | -4 | -3 | -2 | -1 | 0 | +1 | +2 | +3 | +4 |
| Mean | -39.8 | -31.1 | -18.9 | -9.1 | 1.1 | 8.5 | 20.9 | 30.2 | 42.2 |
| STD | 0.3 | 0.2 | 0.3 | 0.2 | 0.5 | 0.8 | 1.0 | 0.6 | 0.8 |
| Min | -40.3 | -31.4 | -19.5 | -9.4 | 0.1 | 7.7 | 17.7 | 29.1 | 40.6 |
| Max | -39.2 | -30.6 | -17.8 | -8.4 | 2.0 | 11.1 | 23.8 | 31.3 | 43.7 |
| Range | 1.1 | 0.8 | 1.7 | 1.0 | 1.9 | 3.4 | 6.1 | 2.2 | 3.1 |
| Mean Dev | 0.2 | 0.2 | 0.2 | 0.2 | 0.4 | 0.5 | 0.7 | 0.5 | 0.6 |
| Max Dev | 0.6 | 0.5 | 1.0 | 0.7 | 1.0 | 2.6 | 3.2 | 1.1 | 1.6 |

output of the potentiometer in correspondence of the points where the new transducer registered the values of the magnetic flux corresponding to each of the 9 levels. For each level we identified: (i) the mean value of all the potentiometer outputs associated with that level and (ii) the range of variation, i.e. the interval between the minimum and the maximum of these output values. Also, we computed the mean and the maximum distance of the potentiometer outputs from the expected values corresponding to each of the 9 stations, namely mean and maximum absolute deviation. Results of this test are reported in Fig. 5 and Table 3. Briefly, the magnetic transducer we designed could discriminate between nine positions. The distance between the centers of two consecutive levels was (mean $\pm$ std) $10.2 \pm 1.8$ mm. The average range of variation across the levels was $2.4 \pm 1.6$ mm (max 6.1 mm; $[-3.2; +2.9]$). For each level the mean absolute deviation was always less than or equal to 0.7 mm ($0.4 \pm 0.2$ mm), and the maximum absolute deviation was lower than 3.3 mm ($1.4 \pm 0.9$ mm).

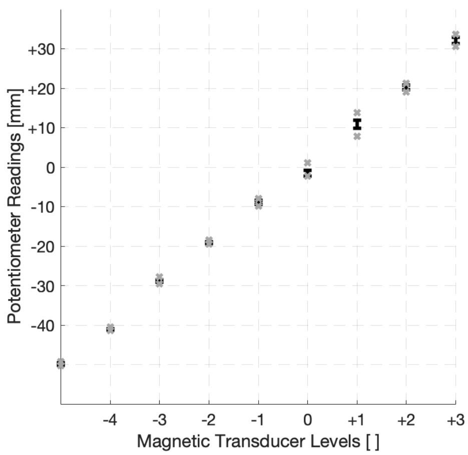


**FIGURE 5. Performance of the magnetic transducer. X-axis shows the nine levels of the magnetic transducer. Each level is labelled with a number corresponding to the engagement level in the birth canal, that is the distance in mm from the ischial spines (level 0). Y-axis shows the measures of the potentiometer. Error bars indicate maximum errors; crosses show the minimum and maximum values of each level across the repetitions.**

This suggests that the magnetic sensors detected different fields with a precision greater than those required by gynecologists and midwives.

## IV. INTEGRATION OF THE MAGNETIC TRANSDUCER IN THE BIRTH SIMULATOR eBSim

As a last step, we integrated the magnetic transducer into eBSim, a low-cost educational tool for midwives and residents in gynecology and obstetrics (Fig. 6) [16], [17]. The simulator combines a physical model with a graphic representation of the birth canal and has a custom-designed user interface. As for the physical model, it includes a model of the pelvic bones and a 3D printed fetal head. The fetal head contains sensors to measure the orientation of the head in the birth canal and detect the user's touch of the two main fetal fontanels [16], [17].

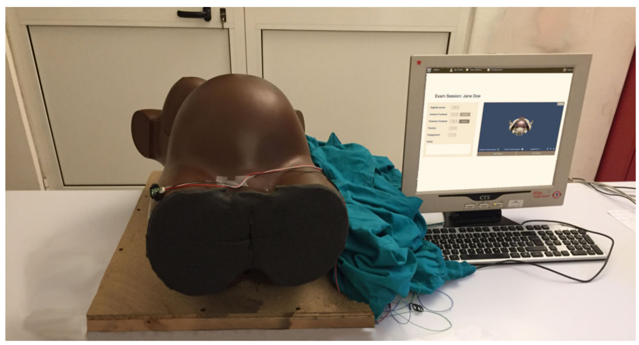

**FIGURE 6. Birth Simulator eBSim. The simulator combines a physical model of a maternal pelvis and a 3D printed fetal head. Sensors in the head send in real time information about its position to a graphic representation which allows the simulator to be used by trainees and instructors.**

The magnetic matrix was installed 205 mm above the ischial spines, on an area outside the birth canal corresponding to the lumbar vertebrae (Fig. 2; Fig. 7a). We selected this position to keep the head and the birth canal clear from any component. In fact, midwives use anatomical landmarks in the fetal and maternal pelvis to determine the fetal position in the birth canal during cephalic deliveries; for this reason, we decided to keep the head and the birth canal clear from any component. We thus installed the matrix 20.5 cm far from the ischial spines, as this distance corresponds to the fetal body, a stable area which is not touched by the student's during the assessment. This would guarantee a fixed placement of both the matrix and the sensors, avoiding accidental movements of the sensors, as well as wires disconnection. Most importantly, the fetal manikins do not have joints which may change the distance or the orientation of the head with respect

FIGURE 7. (a) The magnetic matrix is installed inside the birth simulator eBSim, 205 mm above the ischial spines, covered by a 1 mm soft layer (not shown). (b) Hall-effect sensors used to detect the engagement level of the head. Such sensors are located on the fetus, 205 mm from the biggest diameter of the head. (c) The head is positioned on in the birth canal so that midwives' students can assess the engagement level which is also measured by the magnetic transducer. (d) The fetal position is displayed in real time in a virtual representation.

to the body and the connection between the sensor support located on the body and the head is made with rigid, not deformable material. In this way, it is guaranteed that there is no mechanical displacement and the distance between the measurement point (i.e. the sensors placement) and the head does not vary. Importantly, the magnetic matrix was covered by a 10 mm foam layer mimicking the soft tissues of the birth canal and ensuring a sensor-magnet distance greater than 8.8 mm, that is the lower operational limit of the system.

Nevertheless, the system is flexible and can be adapted to different pelvic models and and fetal manikin by varying the matrix position inside the pelvis and consequently the magnetic sensors location on the baby's body, with the only constraint being the need to maintain a sensors-matrix distance equal or lower than 15.4 mm. Considering the position of the magnetic matrix, we put three magnetic sensors on the fetal torso, 205 mm far from the top of the head (Fig. 7b). The sensors have been connected to an Arduino microcontroller board powered by a lithium battery inside the fetal head.

As for the user interface, the system allows for displaying in real time the orientation of the fetus in the birth canal, receiving data from the sensors. Finally, a desktop/mobile application allows the simulator to be used by students and instructors in different modalities: training, auto-evaluation and exam mode [16], [17]. The visual feedback has been implemented in Unity3D, a cross-platform game engine widely used in gaming, filmmaking, architecture, engineering, robotics, and more generally non-game simulations and visualizations [18]–[21]. The existing software showed in real time the orientation of the fetus in the birth canal and highlighted the fontanels whenever the user touches them. The magnetic transducer installed on the simulator provided the information regarding the engagement level of the fetal head allowing for the correct display the fetus positioning the birth canal (Fig. 7c). In detail, nine Game Objects were attached to the virtual pelvis corresponding to the levels of descent. Hence, the position of the virtual fetus could match, in real time, that of the physical manikin, by translating it toward the Game Object corresponding to the position detected by the magnetic sensors (Fig. 7d).

## V. CONCLUSION

This project sought to design a wireless transducer usable with part-task pelvic trainers to distinguish between nine possible engagement levels of the fetal head in the birth canal. The solution we built is a magnetic matrix, made of 27 low-cost neodymium magnets, which create different combinations of magnetic fields coding nine positions 10 mm apart, detected by three Hall sensors. The system was firstly modelled, then implemented and tested on a custom-made setup, prior to installing it into the existing simulator eBsim. Indeed, our main purpose was to integrate the magnetic transducer on an existing pelvic simulator, to turn anatomical models into sensorized simulators, usable for training and evaluation. Applications as the one proposed in this study can be of broad interest in all the contexts where it is required to detect the position of an object in a small space, discriminating between different possibilities. Most importantly, such system may advance low-fidelity models, turning them into low-cost simulators providing feedback and quantitative evaluation of learners' ability.

### A. INNOVATIVE FEATURES OF THE SYSTEM

The transducer we designed is innovative since it satisfy the following requirements:

#### 1) REDUCED DIMENSION

The system is smaller than a smartphone and does not require a power supply, other than the connections for the Hall sensors inside the fetal manikin.

#### 2) WIRELESS

The absence of any electrical connection inside the pelvic model makes the system easy to install in existing models, maintaining the fidelity level of part-task trainers.

### 3) LOW-COST

The magnetic transducer uses inexpensive permanent magnets to create different configurations of magnetic fields with a precision greater than 10 mm, as well as low-cost Hall effect sensors. Indeed, the overall cost of the transducer is less than 40 USD, perfectly fitting the low-cost requirement.

### 4) EASY TO INSTALL AND USE

Altogether, these aspects make the system usable with many part-task trainers commonly available in simulation centers, medical schools or hospitals. Such models could be turned into sensorized simulators, providing quantitative measure of the engagement level and visual feedback for the trainees, which has been reported to enhance the learning process [22].

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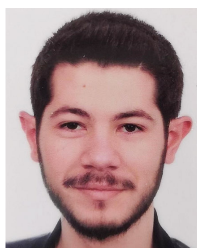

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