Development and assessment of a cyanosis simulator in a fetal manikin for extra-uterine life support innovation

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ABSTRACT

Fidelity is a crucial factor affecting the efficacy of medical simulation training for clinicians. However, the inability of existing manikins to provide a realistic simulation of cyanosis undermines the ability to evaluate skill performance and clinical decision-making adequately. To address this gap, we developed and evaluated four color-changing mechanisms to realistically simulate cyanosis in newborn manikins. The four mechanisms included an electrochromic design using LEDs, a hydrochromic design using colored liquids, and two electromechanical designs using differently colored moving elements. We evaluated the effectiveness of these designs in simulating the correct cyanosis coloration using quantitative color measurements and comparing them with neonatal patient data. Additionally, we performed qualitative assessments with clinicians to evaluate the realism of the simulation. Our results demonstrate that a hydrochromic mechanism provides a realistic simulation of cyanosis coloration, as compared to neonatal patient data and through clinician assessment. Our study addresses the gap in realistic cyanosis simulation in newborn manikins, providing valuable insights for future iterations of medical simulation training for clinicians. These findings will guide the development of new manikins that can provide more accurate simulations, thereby enhancing training outcomes and improving patient safety.

CCS CONCEPTS

• **Sensors and Actuators**; • **Design**; • **Life and Medical Sciences**;

KEYWORDS

cyanosis, manikin, medical training, simulation, extra-uterine life support

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1 INTRODUCTION

Cyanosis is the slightly bluish discoloration of the skin and mucous membranes caused by decreased amounts of oxygen bound to hemoglobin in the erythrocytes [1–3]. Whereas oxygenated hemoglobin is bright red, giving the infant a pink skin, low levels of hemoglobin result in a dark blue or purple skin tone [3]. This phenomenon can be classified into peripheral and central cyanosis [3]. Peripheral cyanosis is the discoloration of the extremities and is relatively common in newborns at birth [3]. In contrast, the presence of central cyanosis (visible in mucous membranes, tongue, and mouth linings) signals the presence of a potentially serious and life-threatening condition and typically necessitates immediate assessment [3, 4]. Typically, newborn infants exhibit cyanosis for several minutes after delivery, but once the oxygen saturation rises above 85%, the cyanosis fades away [4–6]. Persistent cyanosis is a serious condition that requires rapid treatment [3]. The shortage of hemoglobin in the blood may be assessed using pulse oximetry, a standard instrument for evaluating the oxygen saturation of hemoglobin. If the oxygen saturation is at least 60%, it is possible to estimate the oxygen saturation with sufficient precision [6]. Because cyanosis can often be visually assessed, a physical examination is performed before using other methods. This physical examination of the neonate is being performed using the APGAR score criteria, a method to assess signs of hemodynamic compromise [7]. One of the criteria is Appearance, i.e., skin tone, and determines whether cyanosis is present. Preterm newborns are more often diagnosed with central cyanosis compared to term infants [8]. This could be due to the fact that extreme preterm infants often have underlying pathologies affecting oxygen saturation, such as Respiratory Distress Syndrome (RDS), which results from the immaturity of their lungs [9]. Since cyanosis among new infants could be an early sign of underlying pathologies, such as lung disease and congenital heart pathologies, it is essential to determine the occurrence of cyanosis with viable tests and to prescribe effective treatment upon accurate diagnosis [2].

1.1 Medical simulation

Simulation-based training is frequently used in healthcare to practice realistic and complex scenarios in a simulated environment to improve clinicians' performances and ensure patient safety [10, 11].

Within these simulation sessions, manikins of human patients are often used with specific functionalities and/or pathologies.

The participants can develop their clinical reasoning and train their critical decision-making skills in a low-risk environment [12]. 'Suspension of disbelief' is one factor contributing to the improvement of fidelity. Suspension of disbelief focuses on convincing the trainee to forget that he or she is in a simulated setting and to be as committed as in a genuine emergency [13]. If the simulator and training environment are realistic and of high-fidelity, it is easier to suspend disbelief [13]. There are two main types of fidelity known for (medical) simulators: functional and physical fidelity [14, 15]. Physical fidelity encompasses i.e., visual stimuli and could include the external appearance of a manikin, such as its skin color or other signs of symptom display. Functional fidelity relates to the 'act and feel' of the simulator and whether the simulator responds in a realistic manner [15].

1.2 Simulation of cyanosis

Due to the slight discoloration of the skin, the dynamic occurrence of cyanosis is particularly difficult to notice; this study aims to develop a simulation of central cyanosis in an infant manikin to help clinicians recognize and manage this condition more adequately by training the visual assessment of the skin. Since the realism of cyanosis simulation is affected by both functional and physical realism, developing a high-fidelity simulator would be beneficial. Previous scientific work on the simulation of cyanosis has focused on the accurate measurement of the color space of cyanotic skin. For this, a method was developed to measure and determine cyanotic coloration quantitatively [4]. In the study by Azmi, the CIELAB color space is used (compared to other color spaces such as RGB, HSV, and Yxy) as the coloration of cyanosis appeared to be quantifiable in this color space [4]. The depiction of a CIELAB color involves three values, L*, a*, and b*, which correspond to perceptual brightness and the four distinct hues of human visual perception, red, green, blue, and yellow. CIELAB is perceptually uniform; any numerical change would result in an equivalent perceived modification in color. Previous research has shown that the CIELAB color space is adequate for skin color assessment [16, 17]. Still, no functional implementation of these color values has been made into a neonatal manikin. Since the 1960s, manikins for simulation-based teaching have been developed [18]. While certain existing high-fidelity manikins can display cyanotic skin, none of them are described to be based on color measurements retrieved from clinical data. Nevertheless, dynamic, color-changing functionalities have been accomplished in the NENASim Infant (Medical-X, the Netherlands), which can demonstrate both central and peripheral cyanosis as well as a healthy skin tone. Also, the Newborn TORY S2210 (Gaumard Scientific Company, USA) can demonstrate a range of skin tones, from pink to mild and severe cyanosis. Unfortunately, the cyanosis in these manikins appears in the incorrect locations, around the cheekbones. In addition, it looks unrealistic because of the glare of the Light Emitting Diodes (LEDs), and with the LEDs appearing as a light point source. Therefore, despite the apparent promising implementation of LED-based mechanisms for cyanosis simulation in multiple studies, its realism still needs to be improved [4, 19].

The manikin developed in the context of this research will be used to develop and train usage with extra-uterine life support system technology [20, 21]. Such a system is a biomimetic alternative to current neonatal incubators for extremely preterm infants by making it liquid-based [22]. During the delivery of the infant into an extra-uterine life support system, pulse oximetry might not be continuously available. Therefore, visual assessment (i.e., direct or via a camera) will be useful to train during medical simulations. Consequently, the aim of this research is to develop a functional cyanosis simulation mechanism based on the correct coloration of cyanosis in a fetal simulation manikin.

2 METHODS

2.1 Mechanism selection

To find suitable mechanisms for the simulation of cyanosis, an analysis of mechanisms for color change, or chromism, was performed. Chromism is the phenomenon of a substance's reversible color shift that happens in solids and liquids owing to a structural change [23]. External stimuli alter the structure of the substance, resulting in a change in color. There are many varieties of chromism, named based on external stimulus, i.e., thermochromism, photochromism, and electrochromism. The various mechanisms were analyzed and weighted using a simplified Weighted Objectives Table (WOT) method to assess suitability for cyanosis simulation [24]. Criteria were listed to comply with the application in an extra-uterine life support system context and included: dimensions limit, temperature range, color range, color accuracy, color changing time, safety, availability of technology, required voltage, and ease of implementation in a fetal manikin. Assigned scores were subsequently ranked and gave an indication of success when further developing the mechanism. Mechanisms with a score of zero were disqualified, as well as mechanisms that scored low on safety. Five color-changing mechanisms with the highest scores were selected: (1) electrochromism, (2) hydrochromism, (3) photochromism, (4) thermochromism, and (5) mechanochromism.

To operate the color-changing mechanisms, a selection of suitable actuators was made to be considered during development. The classification included electrical, electromechanical, electromagnetic, hydraulic, pneumatic, and smart material actuators [25, 26]. Additive and subtractive color mixing are the two methods of color mixing. In additive color mixing, light sources are added to the process to create a sensation of color, with the light reaching the eye directly from its source [27]. In subtractive color mixing (Figure 3), the paint, pigments, dyes, or other colorants absorb or subtract some parts of the spectrum and transmit or reflect other parts [27, 28]. The parts of the visible spectrum that are reflected when absorption takes place is the color that is determined [28]. In this mode, the light is reflected by another object which can alter the color tone of the original source [27].

2.2 Design and development

Ideations on the selected mechanisms resulted in design sketches leading to five physical prototypes. Two prototypes were based on an electromechanical mechanism, one on electrochromism, one on thermochromism, and one on hydrochromism. The prototypes

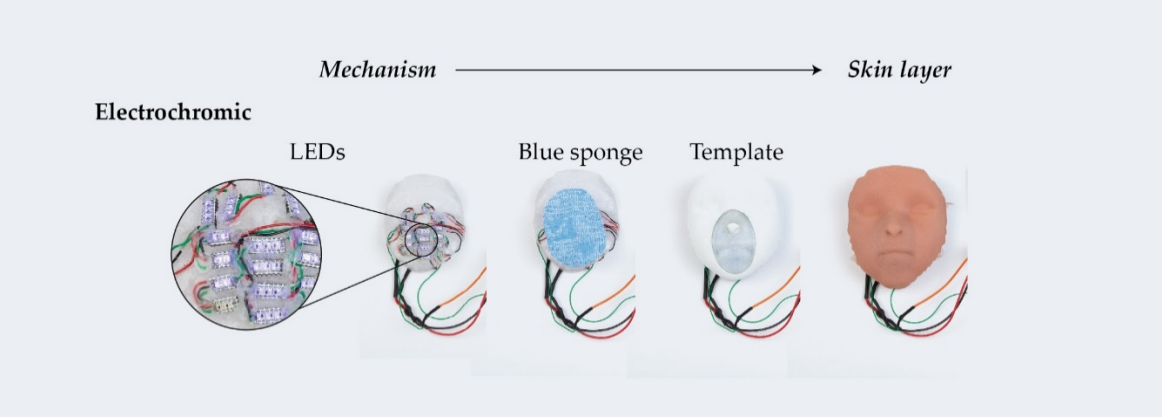

Figure 1: The component layers that make up the electrochromic cyanosis simulator.

were created using a Research-through-Design methodology, gaining knowledge, and understanding through consecutive design iterations [29].

2.2.1 Electrochromic design. The electrochromic prototype uses small LEDs to simulate cyanosis and, therefore, works via an additive color mixing method. The electrochromic design consists of four layers: (1) a 3D printed fetal manikin face with LEDs, (2) a sponge, (3) a 3D printed mask of mixed materials, and (4) a silicone skin layer (see Figure 1). The manikin's face was 3D printed with transparent PETG (Jupiter series, 123-3D, The Netherlands). Glued on the 3D-printed face are custom-made PCBs with connected LEDs (WSB2812 2020 RGB). A digital model of the face was used to determine the correct dimensions of the PCBs and allowed for planning the arrangement of the LEDs. Eventually, two different PCB sizes were designed: 2-LED PCBs and 3-LED PCBs. The LEDs were soldered onto the PCBs, after which the PCBs were glued onto the 3D-printed manikin's face and soldered in series. Multiple ground and 5V cables were attached to ensure enough power ran through the LEDs. In addition, two data cables were necessary because a single data cable resulted in the last LEDs of the series flickering. All electronics were connected to an Arduino Pro Micro (arduino.cc, NY, USA) with a connected button to start the programmed cyanosis code. A sponge layer was added between the LEDs and the 3D-printed mask to make sure that the LEDs would sufficiently diffuse the light, making it possible to brighten the LEDs at the beginning (cyanotic state), after which they can slowly dim (non-cyanosis state). Secondly, when dimming the LEDs, the blue LED stops the fastest (due to the blue wavelength being the shortest), whereas the red LED is dominant. A blue sponge was specifically chosen as the blue material absorbs red and green and reflects blue, overcoming the problem that the cyanotic area will appear red when dimmed. The 3D-printed mask covers the sponge and the 3D-printed face with LEDs. The mask consists of white PLA (polylactic acid filament, Ultimaker, the Netherlands) and transparent PETG (polyethylene terephthalate glycol filament, Ultimaker, the Netherlands), ensuring that cyanosis is only visible in the correct areas. The cyanotic area was determined based on a photo of a neonatal cyanotic patient [4, p. 5]. Software was written to program the LEDs and make them fade away after a set time. Once the button is pressed, the LEDs are turned on, making the cyanosis appear. A random timer between 30 and 60 seconds is started, and after that timer, the LEDs fade away (resulting in the cyanosis fading). For experiment purposes, the timer was set between 30 to 60 seconds to reduce simulation time for the participants. Still, in realistic simulations, this timer could be programmed for an extended duration (between one to ten minutes [4, p. 65]). The choice was made to keep the LEDs active while in the non-cyanotic stage to maintain the additive color mixing mode rather than move between additive and subtractive color mixing (when turning LEDs off) [27, 28]. This ensured that the human eye would be unable to recognize the difference.

2.2.2 Hydrochromic design. The hydrochromic prototype uses colored liquids to simulate cyanosis. Strictly speaking, the term hydrochromic refers to a liquid changing color. This is not the case in this mechanism; however, for clarity, we speak of a hydrochromic mechanism. In a future version, a color-changing liquid could be used.

The design consists of three layers: (1) a cyanotic area, (2) a 3D-printed manikin's face, and (3) a silicone skin layer (see Figure 2). The cyanotic area is designed as a cavity and 3D-printed in a transparent resin (Clear Resin, Formlabs, USA). The back of the model has two openings to which silicone tubes (diameter 4/6 mm) are connected. One of the silicone tubes was necessary to remove trapped air when initially filling the cavity with liquid. The top tube was zip-tied after filling. This resulted in an airtight construct that could be operated using a syringe. The colored liquid was made from water mixed with food dye. The water and dye ratio used was 100 ml of water, 0.35 ml of red dye, and 0.1 ml of blue dye, which resulted in a CIELAB value of L* 13, a* 3, and b* -7. The cyanotic area was placed inside a transparent PETG 3D printed manikin's face (Jupiter series, 123-3D, The Netherlands).

2.2.3 Thermochromic design. The thermochromic prototype employs temperature-sensitive pigment that temporarily changes color when exposed to heat. To test this approach, a custom-made heat element was covered with polyimide foil (Kapton, DuPont, USA) to fit in the contour of the cyanosis region and could be placed

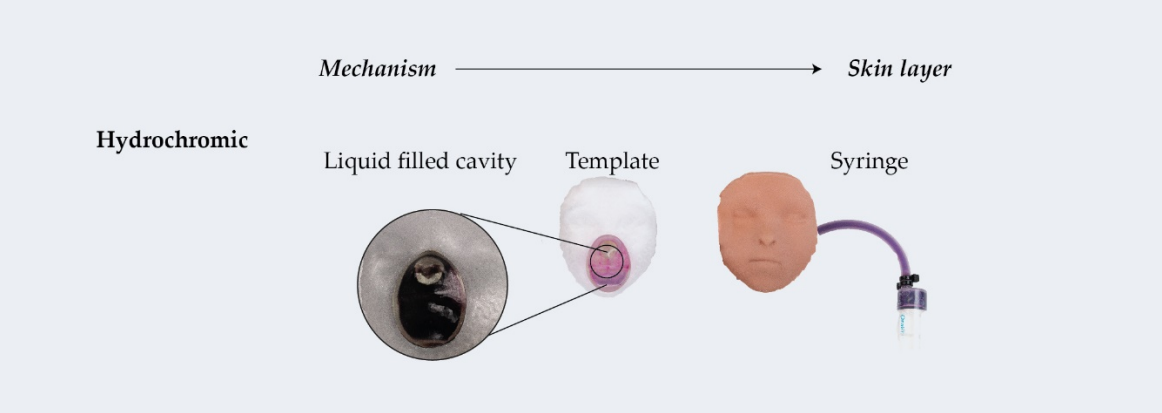

Figure 2: The component layers that make up the hydrochromic cyanosis simulator.

underneath a layer of silicone skin. The silicone skin layer was mixed with black thermochromic pigment (Hali Industrial, China) that would change from black to white at 40 °C. In a default state of cyanosis, the polyimide foil could be inactive, whereas if the cyanosis faded out, the foil would need to be heated.

Although the first iterations were positively visually assessed by the researchers, several downsides of this mechanism became apparent. First, in the context of this research, the fluid in which the manikin will be placed has a temperature of 37 °C which could interfere with the working range of the pigment. However, a thermochromic pigment working in a different temperature range (i.e., 50 °C) could solve this. Secondly, the heating element could also disrupt other functionalities of the manikin (such as interference with integrated temperature sensors). And lastly, over time, the quality of the thermochromic pigment will likely diminish, making the simulation unreliable and in need of more frequent maintenance compared to other mechanisms. For these reasons, the continued development of this mechanism type was halted.

2.2.4 Electromechanical design. This electromechanical design simulates cyanosis through a 3D-printed purple dome with controllable white slats covering the dome. The flexible slats are connected to four stepper motors that, upon rotation, can make the purple cyanosis coloration visible and invisible. The prototype consists of five parts: (1) cyanotic dome, (2) flexible slats, (3) transparent dome, (4) manikin face, and (5) silicone skin (see Figure 3). The cyanotic dome is a 3D model printed with matte grape-like purple PLA filament (Real Filament, The Netherlands) with a CIELAB value of L* 18, a* 19, and b* 6. The final round dome shape was determined through an iterative process, as the purple color needed to be as close as possible to the transparent surface to be visible. Inside the dome, four stepper motors control the cyanotic state. The flexible slats are 0.5mm thin and 3D printed in white TPU (thermoplastic polyurethane filament, Ultimaker, The Netherlands). Through iterative printing and testing, the models resulted in a final shape. The slats were printed flat and were reshaped (heat molded) to the bent shape of the cyanotic dome to ensure smooth movement and prevent friction. Subsequently, the slats were glued to the stepper motor pins. The flexible slats were guided in the right direction using a transparent cover dome (Clear Resin, Formlabs, USA) to avoid contact of the slats with the silicone skin (which results in too much friction). Lastly, the transparent dome could be fitted inside the manikin's face (white PLA, Ultimaker, The Netherlands), with a lasting distance of 2 mm between the transparent and purple dome. The stepper motors were coupled in pairs to DRV8833 bipolar motor drivers, which were then connected to the Wemos D1 Mini (an ESP-8266EX microcontroller). These stepper motors had to be set up in a way that made the change from cyanosis to non-cyanosis seamless.

2.2.5 Electromechanical design II. The second electromechanical design prototype simulates cyanosis through a rotating cone – resembling a spinning top – which has a gradient of color tone from non-cyanotic to cyanotic. To avoid obstruction and friction with the silicone skin suit, the cone is covered by a transparent cover. The prototype consists of three parts: (1) the cone, (2) the multi-material face part with a transparent cyanotic area, and (3) the silicone skin (see Figure 4). The cone was 3D-printed in white PLA (Ultimaker, The Netherlands) and was covered with paint to create a gradient from white to cyanotic tone (cyanotic tone consisted of the color L* of 20, a* of 27 and b* of -28). The cone was dimensioned and positioned in such a way to minimize the distance between the skin and the cone. Within the cone, a metal axis was assembled, of which one side was placed in a designed notch at the back of the 3D-printed face. The other end of the cone was attached to a servo motor (Bluebird BMS-101 DMG, Blue Bird Technology, Taiwan), connected to an Arduino Uno. The face part was 3D printed (Objet Connex, Stratasys) in two different materials, a transparent cyanotic area and a white face part (VeroClear and VeroWhite, Stratasys).

2.2.6 Skin layer. A pre-existing 3D model of a neonate was remodeled and used as a foundation for the manikin's skin. Facial features were reconstructed using a semiautomatic pixel density-based process using the Materialise software package (Materialise NV, Leuven, Belgium) and 3ds Max (Autodesk, California, USA). A 3D print (Objet Connex 350, Stratasys, Israel)) was used to develop a mold that could be used to cast a silicone manikin (Ecoflex 00-30, Smooth-on, USA) using a vacuum casting machine (340 Multiplex, Schuchl, Germany). To develop a 1 mm thick skinsuit, an inner

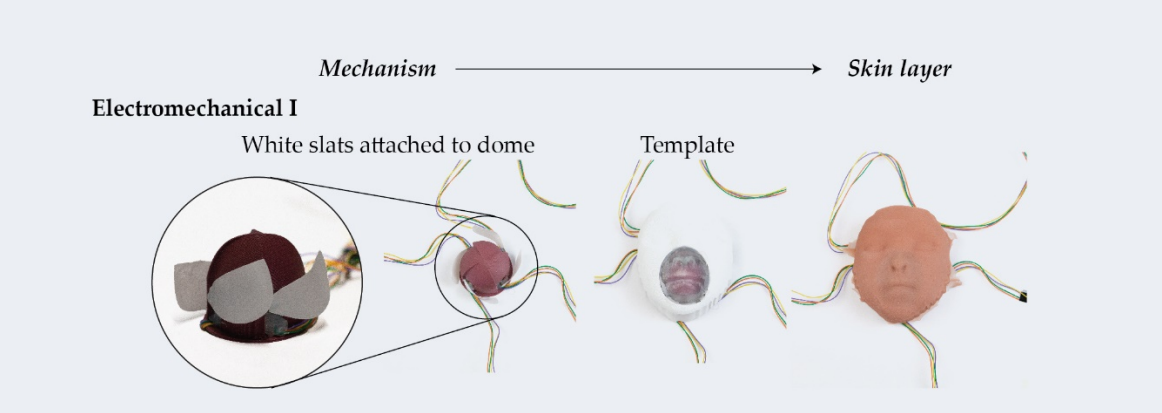

Figure 3: The component layers that make up the electromechanical cyanosis simulator.

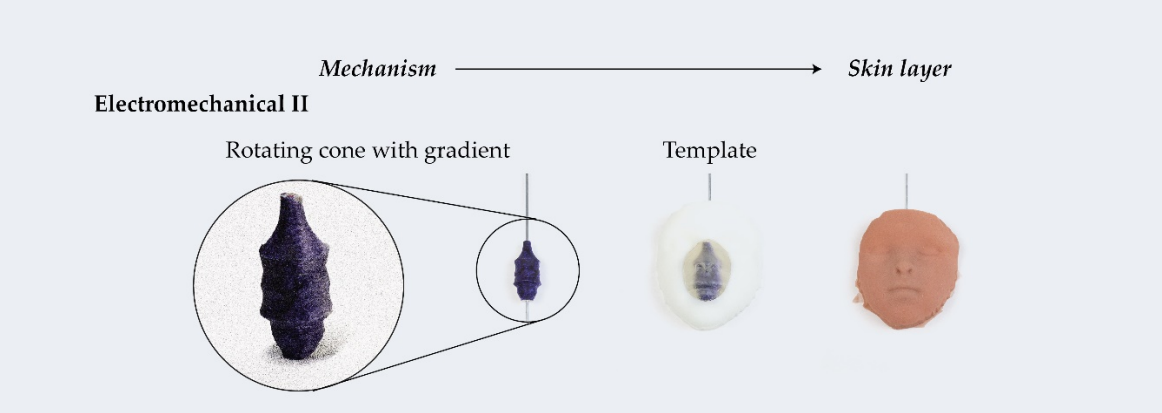

Figure 4: The component layers that make up the electromechanical II cyanosis simulator.

mold was used with a 1 mm offset and suspended in the outer mold. For the pigmentation of the skin into a realistic color, the following ratio was used: 100 ml of silicone with 7 drops (0.24 g) SilTone medium skin tone pigment for 3 drops (0.1g) SilTone fresh blood pigment (SilTone, FormX, the Netherlands).

2.3 Evaluations

Four of the five prototypes were further evaluated; the thermochromic design was not part of the assessment. A mixed-methods technique was utilized to analyze quantitative and qualitative data to determine which mechanism could best simulate cyanosis [30]. Laboratory color measurements of the prototypes were compared with previous research findings [4] to ascertain the realism of the color tone. Evaluation with experts provided qualitative and quantitative data and ensured additional insights about the designed prototypes.

2.3.1 Color measurements. Lab color measurements were performed using a MacBeth color checker (Color Checker SG, Calibrite, USA), a color calibration tool. This was done to establish a reference color value that would allow for the correlation between the color value in the image and the authentic color. The color checker was positioned next to the prototypes when photographed. Photographs were taken with a Canon 70D under consistent light circumstances with fluorescent lamps (see Figure 5). Photographs were imported into Adobe Lightroom to be converted into DNG files and were re-imported into ColorChecker Camera Calibration software (ColorChecker Camera Calibration v2.3.0, X-Rite, USA). Calibrated images can be found in Supplement 1. The created profile was subsequently imported into Adobe Photoshop. The Adobe Photoshop environment was set to the Lab Color space. To assess the cyanosis consistently, a mask of the region of interest (ROI) was created (Adobe Photoshop). This ROI was based on the study of Azmi [4], who determined six landmarks based on standard face landmarks used in face anthropometry. Using Adobe Photoshop's color sampling tool, the L*a*b* values of all landmark points were determined, resulting in six cyanosis coloration values for each prototype.

The six measured colors for each obtained prototype were used to generate scatter plots. A scatter plot was created comparing the cyanotic versus non-cyanotic data from Azmi [4, p. 116] with the data acquired in this investigation. In addition, the measured colors of all prototypes are visualized in a color palette to give an overview (see Supplement 1).

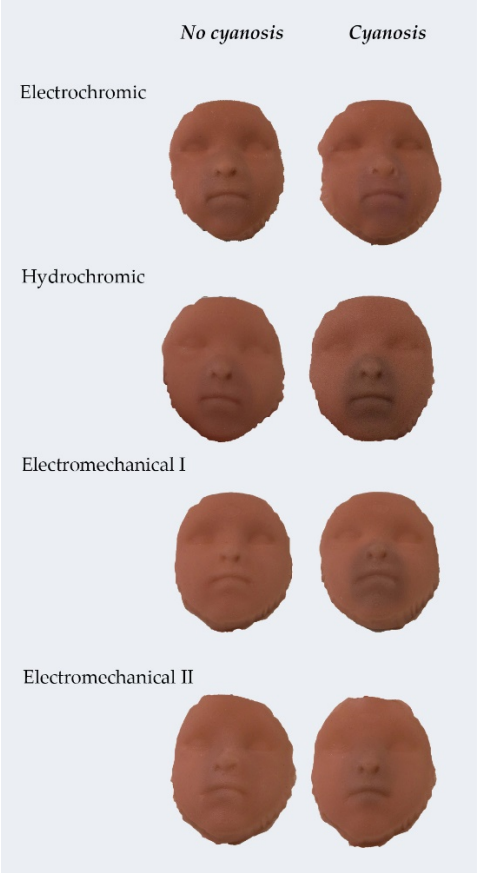

Figure 5: The (non) cyanosis modii of the different mechanisms.

2.3.2 Expert evaluation. Seven clinicians, or clinicians in training, were included in this study (P1-P7). All participants had experience assessing cyanosis coloration in newborns and work either in the neonatal intensive care unit (P1-P3) or the obstetrics department (P4-P7). Participants were recruited through snowball sampling, using a non-probability, purposive sampling method [31]. Prototypes were all assessed in the Maxima Medical Center (Veldhoven, the Netherlands), in similar lighting environments where the prototypes were placed on a white A3-sized paper. In the study, a realism assessment (see Supplement 2) was conducted with both open and closed-ended questions [32]. Closed-ended questions consisted of a 7-point Likert-scale for each of the prototypes [32].

7-point Likert items were chosen, as these have more sensitive degrees of assessment, include odd-numbered so participants can choose a neutral answer, and these have been used commonly in simulator realism assessments [32]. Questions were grouped into the following categories broadly covering physical fidelity and functional fidelity: anatomy, function, performance, and value for training, which were based on existing medical simulation realism assessments [32, 33]. For each feature, an importance rating was given to assess participant perceptions of the significance of each simulator aspect. This could help set priorities in subsequent prototype iterations. A complete list of all questions can be found in Supplement 2. The evaluation duration took approximately 15 minutes per participant. During the evaluation, audio was recorded, for which participants gave consent. Of the ordinal data, the means and SD for each aspect were calculated, and the open-ended questions were analyzed to discover additional insights or alternative responses to the Likert-type data.

3 RESULTS

The final prototypes of the different mechanisms can be seen in Figure 5, with the different layers being covered with silicone skin – all in a non-cyanotic and cyanotic state.

3.1 Color measurements

An analysis was conducted to determine whether the designs exhibited accurate cyanosis coloration based on quantitative measurements during the color measurement process. The measurements obtained for all designs were plotted in a scatter plot (see Figure 7) and compared with data on cyanosis to non-cyanosis (points 1 to 7) previously collected by Azmi [4, p. 116]. The six measured landmarks for each prototype were translated into scatter plots (see Figure 6). Collected data is compared to the reference data from cyanotic patients from the study of Azmi [4, p. 116]. In addition, the measured colors of each mechanism are visualized in color palettes (see Supplement 1).

Figure 6 shows that the electrochromic design falls within a CIE L* difference of approximately -7 to +10 from point 1 (cyanotic stage). When looking at CIE a*, the electrochromic design falls within a difference of approximately -9 and -6 from point 1. For CIE b*, this is -3 to 0. The hydrochromic design falls within a CIE L* difference of approximately +3 to +15. For CIE a*, this is -3 to +2, and for CIE b*, this is -3 to -1. A difference of -6 to +4 for the CIE L* values of the electromechanical I design can be found. For CIE a*, this is -4 to -2, and for CIE b*, this is -5 to -2. Lastly, the difference for the electromechanical II design in CIE L* is -5 to +5, CIE a* is -7 to -3, and CIE b* is -7 to -2. When comparing the CIE a* and CIE b* space for all mechanisms, the landmarks measured of the cyanotic-state hydrochromic mechanism are nearest to the cyanotic state of the reference data. The electrochromic design shows the largest deviation from the reference data. The CIE a* values are especially higher than the reference data, which indicates that the mechanism produces a too magenta-hued color [34]. In contrast, the electromechanical mechanism appears to be too yellow-toned and slightly too magenta.

3.2 User tests

The findings of each Likert-scale question from all prototypes were calculated and combined in Table 1. Score 1 means ‘strongly disagree’, and 7 means ‘strongly agree’. In terms of anatomical realism (color tone, cyanosis area, and overall realism), the highest scores were rated for the hydrochromic prototype and the lowest for the electrochromic. Regarding the appearance and disappearance pattern, the hydrochromic prototype scored highest, and the electrochromic and mechanical II prototypes scored lowest. The educational and scientific values were rated roughly equally among the different prototypes, with mechanical II receiving the lowest

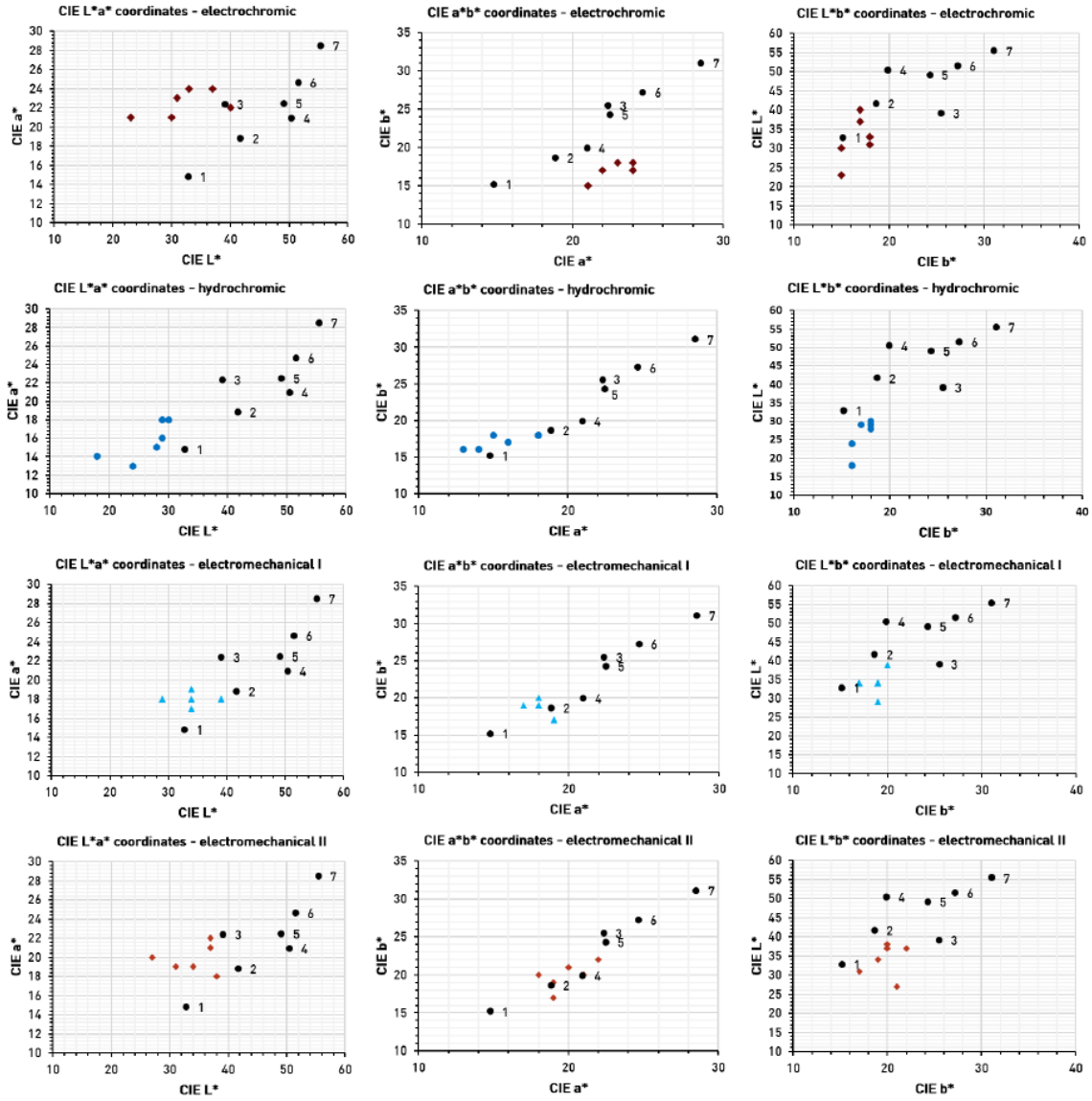

Figure 6: Scatter diagram (in CIE L* and a* and b*) of the electrochromic mechanism cyanosis color measurements versus the human patient cyanosis color measurements of Azmi [4, p. 116]. Points 1 to 7 indicate the presence to absence of cyanosis.

rating. The importance scale was rated rather homogeneous among the different subcategories.

According to the analysis, all participants felt that the hydrochromic prototype simulated cyanosis best. P1 stated: "This [hydrochromic] prototype certainly has potential; it is much more realistic compared to prototype 1 [electrochromic]. The lips are in a good shade of blue". P2 said: "The [hydrochromic] prototype is very subtle, which is like cyanosis, also subtle." "The color of the [hydrochromic] prototype is very good, realistic.". Regarding the disappearance and appearance, P5 said: "The [hydrochromic] prototype is slowly changing, that is nice". P6 said: "Even though the [hydrochromic] prototype is much more subtle [compared to the electrochromic prototype], I see the difference between a cyanotic and non-cyanotic stage." Although all participants stated that the hydrochromic design showed the best cyanosis coloration, aspects were mentioned that would need improvement. P1 said: "I find the subtlety to be much better here [compared to the other prototypes], but the contrast is slightly too little".

The electrochromic design had several disadvantages to its design. P1 said: "It should be more subtle, it is too neon" and ". . .the contour, the area is too symmetric" "That cyanosis is occurring is evident, but it is not realistic." Other comments were made regarding the non-cyanotic stage. P2 stated: "The [electrochromic] prototype stays a bit too gray after the cyanosis has disappeared" and P4: "The non-cyanosis state still shows a bit of different color tone in the cyanotic area."

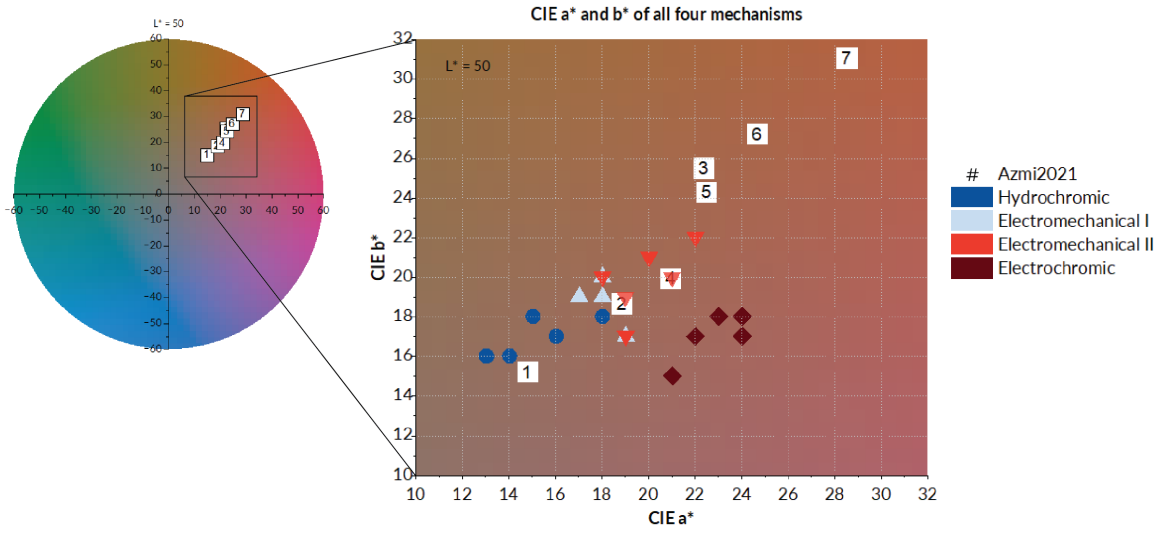

Figure 7: Scatter diagram of CIE a* and b* for all mechanisms in this study in a cyanotic state versus the cyanosis color measurements of Azmi [4, p. 116]. Points 1 to 7 indicate the presence to absence of cyanosis, in which point 1 is cyanotic and 7 is non-cyanotic.

Table 1: Questionnaire scores per mechanism

	Questionnaire scores(**Mean**, SD)				Importance(mean)
	Electrochromic	Hydrochromic	Mech I	Mech II	
Anatomy					
1. Coloration realism	**4.6**, 1.5	**6.1**, 1.1	**6.1**, 0.7	**5.1**, 1.2	**5.3**
2. Area realism	**4.9**, 1.7	**6.1**, 0.4	**5.5**, 0.5	**4.6**, 1.3	**5.3**
3. Overall realism	**4.3**, 1.4	**6.1**, 0.7	**5.5**, 1.1	**5.2**, 1.1	**5.4**
Function					
4. (Dis)appearance realism	**3.9**, 1.2	**6.4**, 0.5	**5.9**, 1.0	**3.4**, 1.8	**5.4**
5. Gives valuable information	**6.2**, 0.4	**6.2**, 0.8	**5.8**, 0.4	**5.0**, 1.8	**5.7**
Education/scientific value					
7. Training	**6.2**, 1.1	**6.2**, 0.6	**6.2**, 0.6	**5.4**, 1.8	**5.7**
8. Decision-making skills	**5.9**, 0.9	**6.1**, 0.7	**6.4**, 0.9	**5.4**, 1.5	**6.1**
9. Treatment development	**5.1**, 1.3	**5.9**, 1.0	**5.9**, 1.0	**4.7**, 2.1	**5.6**
Overall Means	5.1	6.1	5.9	4.8	

Also, the facial area displaying cyanosis was mentioned, with the hydrochromic prototype appearing more realistic than the other prototypes. P3 stated: "In the [electrochromic] prototype, the area is too sharply contrasted with the rest of the face." P4 mentioned "The area of cyanosis in [the electrochromic] prototype is too perfectly framed. P1 stated said: "The area of the face [in the electromechanical I prototype] resulting in cyanosis is too large". "The overall area of the electromechanical II prototype is also a bit too large". And P2 mentioned "The vagueness of the contour of [the hydrochromic] prototype is better compared to the electrochromic prototype". P3 said, "There should be more cyanosis at the lower lip, and less above the nose [in the electromechanical II prototype]".

4 DISCUSSION

The objective of this research was to identify a mechanism that can accurately replicate the cyanosis coloration in fetal manikins, specifically within an extra-uterine life support system simulation context. Prior research has explored diverse functions and applications of neonatal simulation [35]. However, a realistic mechanism for simulating cyanosis has yet to be developed [4]. The present research demonstrates that through the employment of

a hydrochromic mechanism, the manifestation of cyanosis can be realistically simulated. The color measurements acquired for each design are compared with the data presented by Azmi [4]. The findings derived from that assessment suggest that it is feasible to realistically replicate the coloration of cyanosis in neonatal manikins. Implementing a hydrochromic approach would be the optimal mechanism for simulating cyanosis. This assertion is also supported by user tests, which demonstrate that the hydrochromic design exhibited the most realistic cyanosis simulation. Through the user questionnaires and interviews, all participants stated that the hydrochromic prototype showed the most realistic cyanosis overall. This was also mentioned for the subcategories color tone, facial area, and (dis)appearance pattern (see Table 1). Color tone was assessed as quite similar in the different prototypes except for the electrochromic prototype, which appeared too bright and neon. The subtlety of the color and the vague contour of the facial area of the hydrochromic prototype was regarded as very realistic. Also, the (dis)appearance pattern was considered important, especially when seeing the electromechanical prototype II in which the movement appeared unrealistic. Implementing a liquid-based chromatic approach elicits fabrication-related challenges, with an electromechanical (I or II) approach being easier to implement. For this latter mechanism, the coloration must be adjusted to lower CIE a* and b* values. The electromechanical mechanisms were in the range of the reference values [4] but rather near timestamps 2 to 4 instead of 1 (fully cyanotic). The electrochromic mechanism was least competent at simulating a realistic cyanotic color. Predominantly the CIE L* and a* values of all landmarks were inaccurate compared to the reference data. Light emitted by the RGB LEDs had a shorter wavelength [27, 28]. As a result, when the LEDs were dimmed, the blue light was the first to cease, leading to a shift towards redder light (a higher a* value, [34]). Consequently, creating a darker blue/purplish hue was unattainable due to the imperative need to minimize the dimness of the LEDs.

The cyanosis mechanism is intended to be integrated into a fetal manikin with other functionalities to develop, validate and train for extra-uterine life support treatment of preterm infants [36]. The inclusion of such a cyanosis simulator would be insightful for understanding the condition of the infant. Yet, it should be noted that extremely preterm infants are nearly always born cyanotic [8]. Therefore, the fading out of cyanosis (or the difference between cyanotic and non-cyanotic stages) might be predominantly valuable in this case.

Within this context, integrating other components in the facial area of the manikin necessitates the efficient use of space; the embedding volume for actuators is small. Having an anatomically realistic upper airway and oral cavity in the manikin might be useful. In this case, certain mechanisms would be incompatible with this requirement (electromechanical mechanisms), whereas others would allow for this integration (thermochromic or electrochromic mechanisms).

Incorporating the mechanisms into a complete anatomical model could necessitate the inclusion of a power source and a microcontroller, both of which would require designated space. The electromechanical designs I and II employ stepper and servo motors as the actuator driving the color-changing mechanism. The electrochromic design comprises of LEDs affixed to printed circuit boards, while the thermochromic design involves a heating element. For the hydrochromic design, selecting the most suitable actuator posed several fabrication challenges. To prevent the formation of air bubbles in the liquid, the chamber of the mechanism was rendered airtight, yet this resulted in a need to provide sufficient force to push and pull the liquid from a cyanotic stage to non-cyanosis. This challenge could be overcome by integrating a buffer on one end of the chamber to host the 'residual volume' of air. However, pilot testing this approach resulted in bubble formation in the liquid. Another iteration consisted of working with two colored gels, separated by a ball of foam, that could be pushed through a tubular structure by a rotational pump. This mechanism appeared to work correctly in a pilot run. However, the tubular structure would need to be designed in such a way that is realistic to simulate the cyanotic area, and with proper use of radii to enable the foam separator to pass.

4.1 Limitations and future work

The scope of this study was limited to the analysis of a manikin with only one skin tone to establish a correlation between color measurements and the findings of Azmi's study [4]. Additional research is required to incorporate cyanosis data from neonates with other skin tones into this study's framework. The optimal creation of cyanosis-colored mechanisms (including LEDs, liquid, and paint) is influenced by the pigmentation of the silicone skin, which can be adjusted and optimized to achieve the desired visible cyanosis coloration. Furthermore, the setting in which the cyanosis simulation was assessed might not be equal to the clinical environment. Preterm born infants are often shielded from too harsh light and are kept in dimmed light settings or focused spotlights, which might impact the realistic appearance of the cyanosis simulator. Currently no clear objective metric to define skintone of cyanosis is present, except for one study which reference data was used here [4]. A mixed-methods approach was employed to evaluate the four designed mechanisms, incorporating both qualitative and quantitative data collection methods [30]. The utilization of non-probability sampling methods, along with a limited number of participants, resulted in possible sampling bias and reduced population validity.

5 CONCLUSION

Prior research has offered valuable insights into the color determination of cyanosis but has been limited in its ability to produce a simulator that accurately replicates the condition. The objective of this research was to give an overview of possible mechanisms for cyanosis simulation and identify a realistic mechanism for accurately replicating the phenomenon based on qualitative feedback from clinicians and quantitative color measurements. Different color-changing mechanisms were developed, including electrochromic, hydrochromic, thermochromic, and electromechanical. The findings obtained from the expert evaluation and quantitative color measurements indicate that the simulation of cyanosis can be achieved with a high degree of realism through the utilization of a hydrochromic mechanism. Participants considered aspects such as color, cyanotic area, disappearance/appearance pattern, and the educational and scientific value of the simulator. Within the context of this research, the novel fetal manikin will be used for

life-support technology development and treatment training can be used for simulation in a broader context, such as CPR training or other scenarios where fetal distress must be adequately assessed and treated.

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