# Facial Expression Modeling and Synthesis for Patient Simulator Systems: Past, Present, and Future

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Clinical educators have used robotic and virtual patient simulator systems (RPS) for dozens of years, to help clinical learners (CL) gain key skills to help avoid future patient harm. These systems can simulate human physiological traits; however, they have static faces and lack the realistic depiction of facial cues, which limits CL engagement and immersion. In this article, we provide a detailed review of existing systems in use, as well as describe the possibilities for new technologies from the human robot interaction and intelligent virtual agents communities to push forward the state of the art. We also discuss our own work in this area, including new approaches for facial recognition and synthesis on RPS systems, including the ability to realistically display patient facial cues such as pain and stroke. Finally, we discuss future research directions for the field.

## 1 INTRODUCTION

For more than five decades, researchers in the field of Human-Robot Interaction (HRI) have been building and studying how robots can collaborate with humans, support them with their work, and assist them in their daily lives [92, 101, 160]. For example, autonomous mobile robots work side-by-side with skilled human workers in factories and retail sectors [165]. Social robots inform and guide passengers in large and busy airports [187]. In both clinical and home settings, robots have been used to assist healthcare workers, clean rooms, ferry supplies, and support people with disabilities and older adults in rehabilitation and task assistance [160].

There is emerging interest in using robotics technology to address key challenges in healthcare, particularly those related to the quality, safety, and cost of care delivery. However, there are several key contextual challenges to realizing this vision. One big concern is the rapidly increasing costs of healthcare. For example, in the United States, healthcare is expensive across a range of services including administrative costs, pharmaceutical spending, individual services, and the use of high-income trained healthcare workers [12]. Another challenge is the dynamic nature of clinical environments with occupational hazards that put health care workers at risk of injury and disability [93, 182, 183]. Additionally, the global shortfall in professional healthcare workers with sufficient clinical education and skills is challenging [203].

Providing healthcare systems with robots may help address these gaps. For example, robots can support the independence of people with disabilities by enabling transitions to home based care. Robots can also help clinicians and caregivers with care tasks including physical, cognitive, and manipulation tasks [20, 88, 95, 160, 198], as well as healthcare worker education (See Fig. 1).

Robots can potentially enable healthcare workers to spend more time with patients and less time engaging in "non-value added" physical tasks, and reduce the errors caused by the overburden of these tasks [88, 182]. These physical tasks include transportation, inventory, and spending time searching and waiting [160]. For example, Tug robots [14] are medical transportation robots that autonomously move through hospitals, delivering supplies, meals, and medication to patients.

Moreover, robots can assist in clinical learning. For example, humanoid patient simulators can mimic human function (physiology) or anatomy (biology). Some of these simulators are engineered systems that model information integration and flow to help clinical learners study human physiology. Others present models of human patient biology and cognition to provide clinicians with a platform to practice different skills including task execution, testing and validation, diagnosis and prognosis, training, and social and cognitive interaction.

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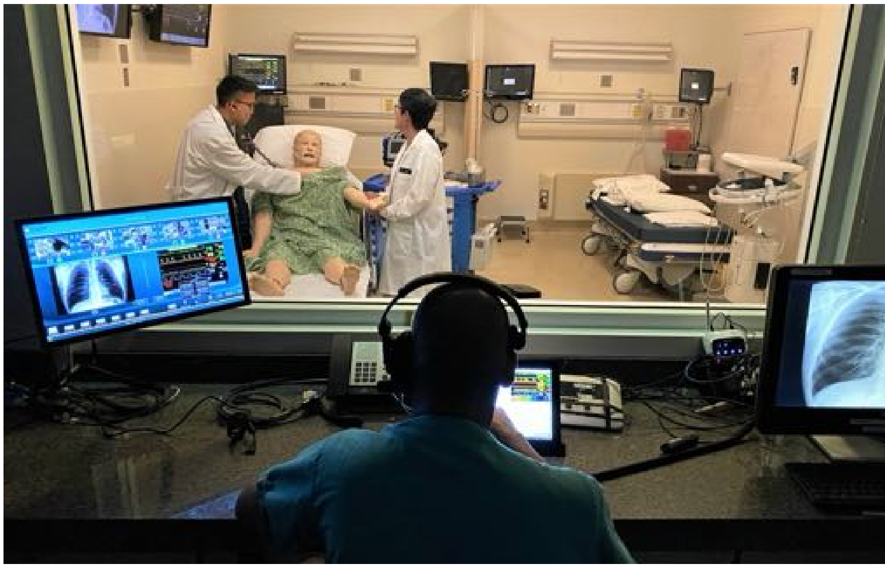

Fig. 1. A typical patient simulation center setup. Clinical learners treat a non-expressive robotic patient simulator. Its physiology is controlled by a clinical educator.

Robotic patient simulators (RPS), virtual patient simulators (VPS) and augmented reality patient simulators (APS) are three main technologies used to represent realistic, expressive patients within the context of clinical education. Clinical educators (CE) can use them to convey realistic scenarios, and clinical learners (CL) can practice different procedural and communication skills without harming real patients.

Although there are many benefits associated with using RPS, VPS, and APS systems, their designs suffer from a lack of facial expressions (FEs), which are both a key social function and clinical cue conveyed by real patients. While enabling RPS and VPS systems with an expressive face can address this challenge, still it creates a bigger challenge with designing expressive systems: facial expressions are very person-dependent and can vary from person to person [212]. It is challenging to analyze, model, and synthesize FEs of a small subgroup of patients on simulators' faces and develop generalized expressive simulator systems that are capable of representing a diverse group of patients (including but not limited to different ages, genders, and ethnicities who are affected by different diseases and conditions) [212].

Another challenge is that incorrectly (or not) exhibiting symptoms on a simulator's face may reinforce incorrect skills in CLs, and could lead to future patient harm. Furthermore, developers may face physical limitations preventing them from advancing the state-of-the-art. For example, VPSs are limited by flat 2D display mediums, making them unable to represent a physical 3D human-shape volume which clinicians can palpate in order to perform clinical assessments. Other challenges include the simulator's usability, controllability, high costs, and physical limitations, as well as the need of recruiting experts with various skills.

Tackling these technical challenges to advance the state-of-the art needs work on several fronts. These include the creation of capable and usable RPS and VPS systems, new techniques for recognizing and synthesizing facial expressions on simulators, novel computational methods for developing humanlike face model for them, and new means for evaluating these systems. Ultimately addressing these gaps can provide healthcare education with realistic, expressive simulators capable of mimicking patient-like expressions. This has the potential to positively affect CLs' retention, and eventually, revolutionize healthcare education.

In this review, we discuss research at the intersection of robotics, computer vision, and clinical education, to enable socially interactive robots and virtual agents to simulate human-patient-like expressions and interact with real humans. In Section 2, we provide an overview of the root causes of preventable patient harm, and contextualize clinical education as a means for addressing it. We outline common learning modalities, including VPS and RPS systems, and outline key opportunities to improve them. Sections 2.4- 5 discuss the importance of incorporating human-like FEs in RPS and VPS systems, and algorithmic approaches for doing so. In Section 6, we discuss our recent research on creating expressive VPS and RPS systems, with diverse appearances and features, which show promise as an important clinical education tool. Finally, Sections 7 and 9 explores open problems in the field and discusses new directions for future work.

## 2 BACKGROUND

### 2.1 Patient Safety and Healthcare Education

The World Health Organization defines patient safety as "the absence of preventable harm to a patient during the process of health care and reduction of risk of unnecessary harm associated with health care to an acceptable minimum" [34]. Taking an action (errors of omission) or inaction (errors of commission) by healthcare workers, system failures, or a combination of these two factors may cause or lead to preventable patient harm [98].

Preventable patient harm represents the root cause of many adverse events experienced in healthcare departments including intensive care units (ICUs), and is a leading cause of mortality and morbidity in the world. Conservative estimates suggest preventable patient harm causes over 400,000 preventable deaths per year in the US hospitals alone [106], and 4-8 million experience serious harm and injury. It is estimated between 27-33% of patients experience an adverse event as a result of their care [9, 69, 175, 190].

While better designed healthcare systems, services, and processes, as well as new technologies, can help reduce the incidence of patient harm, in the short term one of the best approaches is high-quality clinical education. Recent work shows that healthcare education and training is the most effective mechanism to reduce the incidence of patient harm and improve patient safety [166].

One way advance the state-of-the-art of healthcare education is through the development intelligent learning modalities, such as simulation systems. Simulators provide CLs the chance to safely study the causes and effects of errors, while avoiding harm to real patients. Using simulators also improves CLs' comprehension, confidence, efficiency, and enthusiasm for learning [107]. When compared with non-digital learning methods, using patient simulators can more effectively improve CLs' skills, and at least as effectively improve knowledge [112].

CEs may also benefit from using simulation systems to run a variety of desired clinical simulation scenarios on realistic patients based on a learner's need, instead of patients' availability. Examples of these scenarios include nursing simulation scenarios [10], physician scenarios [32], and surgical simulation scenarios [33]. Studies also indicate that using simulation improves the performance of learner evaluation and educational needs diagnosis by CEs [42]. This work, and others, are encouraging, and suggest that augmenting existing healthcare simulation systems with emerging AI-based technologies offers promising opportunities to substantially reduce preventable patient harm, as well as risks to clinicians.

Table 1. Simulators: the structure, functionality, and controlability.

| Type | Medium / Platform | Physiological variables | Visual appearance | Control | Scheduling time |
|---|---|---|---|---|---|
| Standardized human patients (SHPs) | Real: 3D real-human body | Can present some of the variables. | Can display dynamic facial expressions (FEs), gestures, and some of the abnormal visual findings. | Controlled by a human. | High |
| Augmented reality patient simulators (APSs) | Hybrid: Visual appearance projected to a 3D physical surface. | Can easily present all the variables. | Can be programmed to richly display dynamic FEs, gestures, and all abnormal visual findings. | Ranges from fully automated to teleoperated to pre-recorded mode. | Low |
| Virtual patient simulators (VPSs) | Virtual: 2D monitor or TV or Tablet | Can only present the visual physiological variables due to 2D display limitations. | Can be programmed to richly display dynamic FEs, gestures, and all abnormal visual findings. | Ranges from fully automated to teleoperated to pre-recorded mode. | Low |
| Robotic patient simulators (RPSs) | Mchanical: 3D human-like physical robot | Can exhibit 5000+ physiology changes on it. Verbal responses controlled using a live operator. | Mostly have a static face. They can be programmed to display some of dynamic FEs, gestures, and abnormal visual findings. | Ranges from fully automated to teleoperated to pre-recorded mode. | Low |

### 2.2 Patient Simulator Types, Benefits, and Challenges

There are four types of simulated patients used in simulation-based clinical learning: standardized human patients, augmented reality patient simulators, virtual patient simulators, and robotic patient simulators. Table 1 illustrates the structure, functionality, and controlability for each type of patient simulator. This is further discussed below.

**Standardized human patients (SHP)** are live actors who assume the roles of patients. They convey a series of symptoms and/or a scenario defined by CEs [47]. SHPs are beneficial as they provide CLs with a real-human case study to practice their history-taking and clinical assessment skills. As a result, SHPs enable the learning process to sometimes deviate from a predefined senario, as this type of simulator can adapt to unexpected changes on-the-fly.

However, SHPs cannot accurately exhibit many symptoms of real patients, such as facial paralysis or physiological changes. Furthermore, recruiting SHPs can be difficult and expensive, especially ones at younger ages because of child labor laws and scheduling difficulties [41, 47, 91, 188].

**Augmented reality patient simulators (APS)**, also known as physical-virtual simulators, use augmented reality (AR) techniques to combine physical human-shaped surfaces with dynamic visual imagery projected on its surface [72]. APSs combine the benefits of two worlds: its physicality can convey a realistic, embodied similarity to people, while its virtual component can display dynamic appearances and FEs without being limited by hardware infrastructure.

However, it is still challenging to display an accurate representation of naturalistic symptoms even in an AR environment. APSs also present some challenges depending on the AR modalities and techniques used. Recent work [63] suggests to avoid the use of commercially available head-mounted displays for augmented reality surgical interventions, because perceptual issues can affect user performance. In front-projected imagery (FPI) [163], the shadow of users can hover over the