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REVIEW

More than surgical tools: a systematic review of robots as didactic tools for the education of professionals in health sciences

Samuel Marcos-Pablos[1] · Francisco José García-Peñalvo[1]

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Abstract

Within the field of robots in medical education, most of the work done during the last years has focused on surgeon training in robotic surgery, practicing surgery procedures through simulators. Apart from surgical education, robots have also been widely employed in assistive and rehabilitation procedures, where education has traditionally focused in the patient. Therefore, there has been extensive review bibliography in the field of medical robotics focused on surgical and rehabilitation and assistive robots, but there is a lack of survey papers that explore the potential of robotics in the education of healthcare students and professionals beyond their training in the use of the robotic system. The scope of the current review are works in which robots are used as didactic tools for the education of professionals in health sciences, investigating the enablers and barriers that affect the use of robots as learning facilitators. Systematic literature searches were conducted in WOS and Scopus, yielding a total of 3812 candidate papers. After removing duplicates, inclusion criteria were defined and applied, resulting in 171 papers. An in-depth quality assessment was then performed leading to 26 papers for qualitative synthesis. Results show that robots in health sciences education are still developed with a roboticist mindset, without clearly incorporating aspects of the teaching/learning process. However, they have proven potential to be used in health sciences as they allow to parameterize procedures, autonomously guide learners to achieve greater engagement, or enable collective learning including patients and instructors "in the loop". Although there exist documented added-value benefits, further research and efforts needs to be done to foster the inclusion of robots as didactic tools in the curricula of health sciences professionals. On the one hand, by analyzing how robotic technology should be developed to become more flexible and usable to support both teaching and learning processes in health sciences education, as final users are not necessarily well-versed in how to use it. On the other, there continues to be a need to develop effective and standard robotic enhanced learning evaluation tools, as well good quality studies that describe effective evaluation of robotic enhanced education for professionals in health sciences. As happens with other technologies when applied to the health sciences field, studies often fail to provide sufficient detail to support transferability or direct future robotic health care education programs.

Keywords Robotics · Health sciences · Education · Training · Systematic review

Extended author information available on the last page of the article

Introduction

Common definitions of robots describe them as machines that resemble a living creature capable of moving independently, performing complex and, often repetitive tasks (Sarrica et al., 2019). Such definitions have a strong bias towards early industrial robots as manipulators that can grasp and move objects in industrial environments. Nowadays, robots can cooperate closely with humans to perform jobs with greater precision and efficiency, for example surgical robots (Bonatti et al., 2021; Chen et al., 2021; Sharma & Bhardwaj, 2021), with an increasing importance since the COVID-19 pandemic.

In fact, in terms of employing robots in health sciences, the field of surgery has been the most active during the last three decades (Ginoya et al., 2021; Leal Ghezzi & Campos Corleta, 2016; Peters et al., 2018). However, robots have been increasingly used in the province of health sciences to perform a wide number of health related tasks (Kyrarini et al., 2021). Apart from surgical robotics, many other classifications have been proposed in the literature for health related robotics (Boubaker, 2020). One of the most widespread of such classifications is the one found in Cianchetti et al., (2018) who categorized health sciences related robotics as: medical robotics (Mapara & Patravale, 2017) including surgery (Collins & Wisz, 2020; Kadakia et al., 2020), diagnosis (Kaan & Ho, 2020; Tavakoli et al., 2020) and drug delivery devices (Mapara & Patravale, 2017; Nguyen et al., 2020); assistive robotics (Giansanti, 2021), such as wearable robots (Bai et al., 2018) and rehabilitation devices (Alias et al., 2017; Mohebbi, 2020), and human body mimicking robots including phantom devices (Hughes et al., 2020; Takeoka et al., 2017) and body-part simulators (Cz et al., 2012; Horvath et al., 2020).

Focusing on employing robots in health sciences education, again most of the work done during the last years has focused in surgeon training in robotic surgery (Collins & Wisz, 2020; Forgione & Guraya, 2017; Kadakia et al., 2020; Khalafallah et al., 2020). In this sense, it is common to practice surgery procedures through simulators, as the handling of robotic surgery devices requires additional skills (Azadi et al., 2021; Badash et al., 2016). In addition, preoperative planning or workflow optimization in the operating room can also be simulated in order to increase patient safety in the context of robotic surgery (Lovegrove et al., 2017). There is also a trend towards a standardized validated robotic surgery training curricula (Altok et al., 2018; Chen et al., 2020a, b), as the majority of current training is delivered with traditional methods such as laboratories that have access to cadavers or phantoms and dedicated training robots (Chen et al., 2020a, b).

In terms of assistive and rehabilitation robotics, education has traditionally focused in the patient, whether from the point of view of improving their quality of life (Gochoo et al., 2020; Louie et al., 2020; Pu et al., 2020), providing them with knowledge about their disease or a medical procedure they are about to undergo (Blanson Henkemans et al., 2013), or focusing on teaching them about the use of an aiding technology, such as wearable or rehabilitation devices (Ciullo et al., 2020; Mohebbi, 2020).

Physical mimicking systems (e.g., phantoms) have traditionally been used in training of medical students, both for diagnosis and practicing medical procedures (Cooper & Taqueti, 2004). However, to date most of these simulation training devices are still merely designed to reproduce the physical properties of tissues, human organs (Altok et al., 2018) or whole body (Wallace et al., 2010).

In terms of survey papers, there has been extensive review bibliography in the field of medical robotics (Cianchetti et al., 2018; Troccaz et al., 2019). Most of the recent surveys focus on surgical robots (Chen et al., 2021; Chen et al., 2020a, b; Gifari et al., 2019;

Simaan et al., 2018; Peters et al., 2018; Díaz et al., 2017) and rehabilitation and assistive robots (Giansanti, 2021; Meng et al., 2017; Mohebbi, 2020; Rupal et al., 2017).

However, based on the existing bibliography, there is a lack of survey papers that explore the potential of robotics in the education of professionals in health sciences beyond the training in the use of the technical system itself (e.g., handling a surgery robotic platform or a rehabilitation device). As other works have shown (Murata et al., 2017; Lee et al., 2020b), the use of robotic technology in health sciences education provides professionals with learning scenarios that are more motivating, collaborative, interactive, and help to make medical training safer and more creative. Moreover, technological enhanced learning approaches have gained even more importance since the COVID-19 pandemic (García-Peñalvo et al., 2020, 2021). Therefore, the aim of the present survey is to explore the use of robotics as didactic tools for conveying learning in health sciences, to gain insights of how robotic technology is being incorporated in the teaching/learning process of health professionals, and if and how robotics is being added to their training curricula as a complement to traditional education methods. Research goals can be translated into the following main research questions: How are robotics considered in the health sciences education literature beyond surgical robots and the manipulation of robotic instruments? How are robotics integrated into the teaching/learning of health sciences? Are there documented added-value benefits of the use of robotics against other approaches?

Putting all together, we were interested in investigating the enablers and barriers that affect the use of robots as didactic tools for the education of health sciences professionals.

Methodology

The following sections describe the process undertaken, which follows the recommendations of the Associations for Medical Education in Europe (AMEE) (R. Sharma et al., 2015), complemented with the recommendations of Kitchenham (2007), Petersen (2015) and (García-Holgado et al., 2020).

Review scope and eligibility criteria

The scope of the current review are works in which robots are used as didactic tools for the education of professionals in health sciences. However, this statement needs more clarification, both in terms of what robots and didactic tools will be considered in the following sections.

Firstly, the review is oriented towards the education of professionals in health sciences, so those studies where robots are used to support professionals in the education of patients are out of the scope of the current review (Gochoo et al., 2020; Louie et al., 2020).

Current review does not consider proposals where there is no "physical" element, for example software robots where an AI (artificial intelligence) system runs on a host computer (Eckert et al., 2019), or virtual representations of robotic devices and/or patients without any type of robotic feedback (Fontanelli et al., 2019; Haji et al., 2021).

Finally, in terms of their use as didactic tools, the inclusion of papers in the current review is determined by the modelling goals of the robot. Robots provide an approximate representation of a real-world process which can be executed to perform a simulation. Within the health sciences field, this representation (model) of the real world can be categorized as (Jörg et al., 2013): (1) application model, that captures the procedure

(Application-Centric); (2) system model, that captures the implementation of the robotic system (System-Centric); (3) patient model, that captures the environment with the focus on the patient (Patient-Centric). Taking the above classification into account, pure system – centric robotic education papers (e.g. providing trainees with skills in the use of a particular robotic device as in (Chen et al., 2020a, b; Khalafallah et al., 2020)) are out of the scope of this systematic review.

In addition, this review does not consider haptic simulators for surgical training, where the physical properties of the human body are parameterized to formulate the haptic model for the surgery simulator. There are various reasons for excluding such studies. On the one hand, the borderline of whether such systems could be considered robotic constructions or software robots with a haptic interface is in many cases unclear. Secondly, it is often difficult to establish if they are system-centric or application-centric didactic tools. Last but not least, there exists extensive and recent review bibliography in the field, as it has been one of the main subjects of technology-related medical education during the last decades (Chen et al., 2020a, b; Ginoya et al., 2021; Sharma & Bhardwaj, 2021; Chen et al., 2021; Bonatti et al., 2021).

Database selection

The databases in which to conduct the search were selected according to the following criteria:

- The database is available for the authors' institutions.
- The database accepts the use of logical expressions or a similar mechanism.
- The database allows full-length searches or searches only in specific fields of the works.
- The database allows additional filtering options such as publication year or publication language.
- The database is one of the most relevant in the main research areas of interest within this review process: education, health sciences and robotics.

Taking the above criteria into account, the search was conducted in the following electronic databases: Web of Science and Scopus. Both databases are commonly used in medicine, as they include most Embase, Cochrane and Medline results. In fact, medicine is the largest category of WoS and Scopus related papers over the last 15 years (Zhu & Liu, 2020). On the other hand, returned results include more knowledge domains than those returned by specialized databases, which a major point considering the interdisciplinarity nature of the current review.

Search string

Several searches where piloted in order to identify which terms added value to the search (see "Appendix 1").

The final search strings used in the search are shown in Table 1. Wildcards were employed to maintain the search broad enough, complemented with proximity operators in such a way that the terms related with education and health sciences do not appear too far apart in the returned papers, and the strings returned a manageable number of results. In addition, while reviewing the piloted obtained results, it was observed that including terms related with simulation biased the results towards non-robotic interfaces. For that reason,

Table 1 Final search strings

Database	Search String	No. Results
WoS	1. (education OR teach* OR learn* OR train* OR instruct*) NEAR/3 (medicine OR health* OR care* OR therapy OR treatment) AND (robot*)	1061
	2. robot* patient simulator	843
Scopus	1. (education OR teach* OR learn* OR train* OR instruct*) W/3 (medicine OR health* OR care* OR therapy OR treatment) AND (robot*)	1425
	2. robot* patient simulator	396

and to include studies related with robotic human patient simulators, a second complementary search was performed which only focused on those terms.

Inclusion and exclusion criteria

The following inclusion criteria (IC) were developed by the two authors (SMP) and (FjGP) and employed to include or exclude a paper from the later analysis. If any of the papers failed to meet the IC, it was not further considered.

- IC1: The papers focused on robotics AND
- IC2: Those robotic solutions were utilized in health sciences education AND
- IC3: The papers were written in English AND
- IC4: The papers were published in peer-reviewed Journals, Books, Conferences or Workshops AND
- IC5: Papers had a document body that was more than three pages long. Papers shorter than 3 pages are excluded from the review to speed up the review process as they are unlikely to fulfil the quality criteria.

Quality assessment criteria

To assess the quality of the primary studies, a quality checklist was developed by the two authors (SMP) and (FjGP). The quality assessment checklist consists of a series of questions to be answered from reading of the paper content. The objective of the checklist was that final included papers were able to provide as much information as possible related to the main research questions, and to avoid subjectivity in the final inclusion of studies in the synthesis. The answer to each of the questions was labeled as Yes/Partially/No and given a score of 0/0.5/1 respectively. The Yes/Partially/No values stand for: Yes = information is explicitly present in the paper; Partially = information is implicit/stated; No = information is not inferable. A score of 6 was used as a cut-off point to ensure that the studies clearly met the criteria, as it was observed that several papers with a score below 6, although related to the study topic, did not contain sufficient information to adequately answer the research questions. The considered checklist was as follows:

1. Are the research aims related to teaching/learning with robots for health science professionals? Y/N/partial
2. Is the use of a robotic platform clearly justified? Y/N/partial
3. Is the robot goal clearly described? Y/N/partial
4. Is the teaching/learning process clearly described? Y/N/partial
5. Is there any kind of evaluation of the teaching/learning process? Y/N/partial
6. Are data on the evaluation of the proposed solution available? Y/N/partial
7. Are metrics clearly described and specified? Y/N/partial
8. Is the proposed methodology compared against traditional teaching/learning approaches? Y/N/partial
9. Are the links between data, interpretation and conclusions made clear? Y/N/partial
10. Is the modelling approach patient or application—centric (not system-centric)? Y/N/partial

Study inclusion

The protocol followed consisted of the main steps as described below. The process was carried out using Google spreadsheets and is available at the following link: https://bit.ly/3eKhD3a1. The search was conducted by the first author (SMP) in the selected databases and using the query strings previously described. All the results were collected in.csv format including title, abstract, authors, publication year, publication venue, etc.

2. The inclusion criteria were then applied by (SMP) to the downloaded list of candidate papers. In those cases where the title and abstract were not sufficient to make a decision, both authors (SMP) and (FjGP) assessed independently the entire content of the paper and discussed its inclusion until a consensus was made. The resultant candidate papers were added to another sheet of the spreadsheet document.
3. The papers were then read in detail and analyzed by (SMP) based on the quality assessment checklist, and the results were collected in another spreadsheet. Additionally, (FjGP) double screened a sample of the excluded papers in step 2. Those papers with an overall score lower than 6 were excluded from the synthesis. Those papers which were instances of the same work were also excluded. Also, (SMP) double-checked that papers with an score higher than 6 clearly met the review scope (i.e. paper describes a physical robot, the robot is employed for the education of professionals in health sciences, robot model is not system-centric), and created an additional spreadsheet entitled "Additionally excluded papers with reasons" for further reference (see https://bit.ly/3eKhD3a). Uncertainties and conflicts with respect to article selection were resolved by discussion between both authors (SMP) and (FjGP).

Following the above steps, the obtained results are shown in Figure 1 which is an adaptation of the PRISMA flow diagram (Moher et al., 2009) and maps out the number of records identified, included and excluded, and the final obtained papers.

Data extraction

A qualitative data analysis approach was followed to extract relevant data from the selected studies. The conducted process followed three major stages:

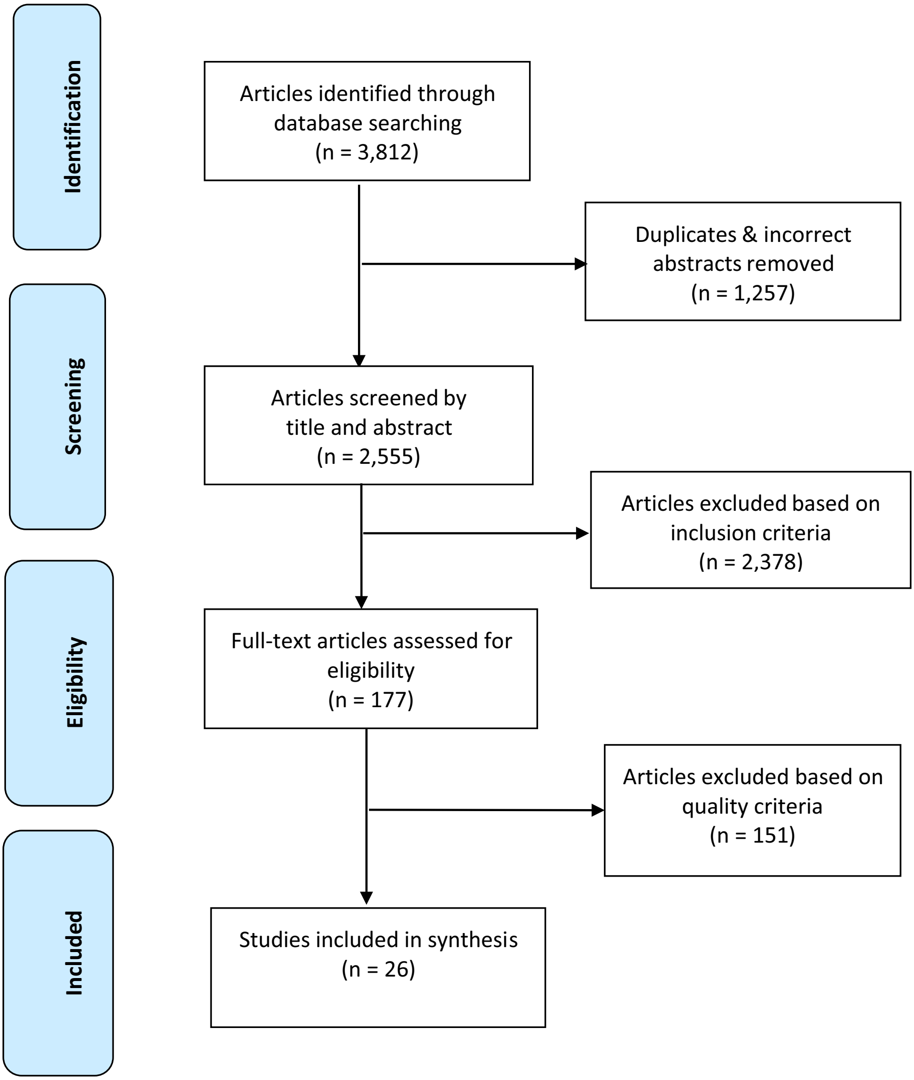

Fig. 1 Steps and results of review and mapping process. Reported as proposed in the PRISMA Statement

1. Papers were first read in detail localizing chunks of text related to each research question and were highlighted for further analysis.
2. Pattern labels to assign symbolic meaning to the highlighted information were created. Related patterns were grouped to find, extract, and categorize the segments relating to a particular research question.
3. A second in depth read of the text was performed and data was retrieved and stored in a spreadsheet (https://bit.ly/3eKhD3a) following the coding created during stage 2.

The following data extraction groups and labels were created by (SMP) and (FjGP) for each research question:

Related to research question 1: How are robotics considered in the health sciences education literature beyond surgical robots and the manipulation of robotic instruments? To answer this question, we considered the robot goal (a general description of the robotic construction); the skills objective of training; the related health sciences field and the target group of health professionals. It has to be noted that, while the health sciences field is easily inferable, because there are countless professional roles in the health sciences, the intent of the target group was to be all inclusive rather than providing specific professional roles.

Related to research question 2: How are robotics integrated into the teaching/learning of health sciences? To answer this second question, we followed the work of (Jörg et al., 2013) related to the use of technology in medical education. We considered three types of training goals (prevention, diagnosis, or treatment); as another category, we labelled the studies that focused on modelling a health procedure as application-centric, and as patient-centric studies those that focused on modelling the patient; furthermore, application-centric models could be related to a concrete task or a complete procedure. In addition, we divided patient-centric studies into general approaches that model the anatomical or physiological properties of the human body, or case-specific if they also incorporate the restrictive parameters caused by a disease or impairment. To extract this information, we sticked to the objectives indicated by the authors even though additional modelling categories and applications could be inferred from the possibilities of the robots developed.

Related to research question 3: Are there documented added-value benefits of the use of robotics against other approaches? We considered whether the teaching/learning process was described in the paper, and if the acceptance of trainees was collected (e.g. questionnaires, discussion groups, etc.). Complementary, and similar to other approaches aiming to investigate the effects of the use of technology in medical education (van Gaalen et al., 2021), we used the framework proposed by Cook et al. (2008) for the classification of the teaching/learning process evaluation. The framework allows to classify the studies as descriptive, justificative and clarificatory. Descriptive studies focus on observation and describe what has been done without making any comparison. Justificative studies make comparisons between interventions, but without a proper conceptual framework which explains the observed effects. Clarificatory studies apply a theoretical background to explain the effects and differences of the interventions and make a clear statement of the future lines of research based on the observed effects.

Results

Results of the extracted data are summarized in “Appendix 2”.

Robot description

Most of the robots used as didactic tools in the studies (n = 22) are robotic instances of what are known as human patient simulators (HPS), differing in the body part they simulate (see”Appendix 2″ for a detailed description). From these, many replicate just extremity joints such as the upper limb (e.g. (Lee et al., 2020a, b)) or the hip and knee (Frey et al., 2006). However, some studies like (Frey et al., 2006) complement the robotic construction with a non-actuated human mannequin to resemble the rest of the human body, and other multimodal feedback channels such as screens or voice synthesis. A variant of these approaches are wearable robots used as impairment simulator of the knee joint (Ishikawa et al., 2015) and ankle + feet (Okumura et al., 2013). In addition, four studies present a robot that resembles the whole human body (e.g. (Lin et al., 2020)) with a varying number of DOFs in each body joint depending on their goal. In (Chihara et al., 2013) and (Moosaei et al., 2017) they present human-like robotic heads, able to simulate the muscle movements of the human face. The number of degrees of freedom (DOFs) simulated in all these robotic constructions is variable, but in general they match the ones of the human joint they simulate.

Organ simulation robots are described in four studies, where the robotic construction models different physiological properties. Usually, these robotic constructions are combined with phantom materials that provide the anatomical resemblance (Formosa et al., 2018).

Finally, two studies (Couto et al., 2017; Sampsel et al., 2014) employ humanoid robotic mobile platforms (with displacement capability), and in (Hong et al., 2019) the robot simulates a hands-on process, in which the pre-recorded movements of an experienced surgeon are transferred to the trainee.

Teaching/training goals

Teaching and training goals are mostly related to treatment training robots. Of these, six focus on manual rehabilitation of extremity joints. Other treatments include dental procedures, cardiopulmonary resuscitation (CPR), radiosurgery, mechanical ventilation, and surgery.

Diagnosis is the training goal of twelve studies. Again, half (n = 6) of those studies focus on the manual examination and diagnosis of extremities. Other studies aimed at training diagnostic skills include endoscopy training as in (Pepley et al., 2016) and colonoscopy training as in (Formosa et al., 2018). Finally, one paper (Moosaei et al., 2017) focuses on enhancing the skills to detect pain in facial expressions.

Fewer studies are focused on prevention. These include (Lin et al., 2020) which aims to prevent harming the patient during transfer to and from wheelchairs; (Couto et al., 2017) focused on the education of health professionals in hand hygiene practices, and (Lee et al., 2020a, b) focused on the prevention of upper-limb joint pain in the elderly by means of exercises. In addition, the goals of (Pepley et al., 2016) and (Formosa et al., 2018) include the early detection and prevention of diseases.

Target groups & health sciences field

Studies target groups correspond to the nature of the robot and the training goals. As such, eleven studies lay in the province of physiotherapy and are oriented to physical therapy related students or practitioners, nine studies are focused on nursery skills development and two relate to dentists and dental assistants. Other specialties include gastroenterologists (Formosa et al., 2018), neurologists (Chihara et al., 2013), and surgeons (Hong et al., 2019). However, while in most cases the health sciences field and related specialty is described by the authors or can be easily inferred, few studies (e.g. (Swain, 2017) for nurse students or (Horvath et al., 2020) for intensive care unit interns) make an explicit distinction regarding the adequate level of knowledge of the target group (e.g. student vs intern vs resident vs fellow vs attending).

Modelling category and level

Nine studies are purely patient centric. From these, eight simulate one or more case specific functional impairments of body joints (e.g. muscle spasticity (Othman et al., 2018), lead-pipe rigidity (Ishikawa et al., 2015) or limitation of motion range (Lee et al., 2020a, b)).

Only application—centric models can be found in eleven studies. Modelled procedures range from tele-rounding in ICUs (Sampsel et al., 2014) to correct transfer of patients to and from wheelchairs (Lin et al., 2020) or protocol when epileptic seizure (Zubrycki et al., 2019). Examples of modelled basic tasks are detect pain in facial expressions (Moosaei et al., 2017) or hand hygiene (Couto et al., 2017).

The rest of the studies include both modelling the patient / symptomatology and the associated procedure, e.g. in (Takanobu et al., 2007), where a human-like dental robot simulator models full body joint movements, facial expressions, eye tracking, mouth movements, and vomiting reflex and blood effusion during teeth drilling. In addition, the robot is remotely controlled by a supervisor to model diverse dental procedures.

Research type & evaluation method

Overall, almost half (n = 11) of the studies are descriptive and analyze the benefits of the robotic didactic tool by means of expert assessment or comparing its performance against data obtained from patients' databases. Eleven studies are justificative, and interventions are composed by students/trainees vs. experts, laypersons vs. experts, between experts, and between students. Evaluation methods are commonly based on questionnaires or analyzing differences in parameterized data captured by the robotic platform. Other evaluation methods include the comparison of stroke patients ability to move an impaired hand before and after following a 60 days recovery program with a robotic intervention (Sharifi et al., 2016) and discussion groups (Swain, 2017). It must be noted that, although proposing a justificative approach, some studies do not specify the number of participants in each intervention (Couto et al., 2017). In fact, only four clarificatory studies were found (Moosaei et al., 2017; Sampsel et al., 2014; Swain, 2017; Wang et al., 2015).

Teaching/learning process

Even though all studies clearly stated the educational goal of the proposed robotic platform, only nine studies describe in greater or lesser detail the teaching/learning process (e.g., teaching methodology, environment configuration, whether the practitioner/student needs directions, if the robot needs to be remotely operated, etc.).

Within those studies that do not describe the educational approach, we can consider Fleming & Mills VARK model (Fleming & Mills, 1992) to infer the learning process based on the robot goal. Therefore, kinesthetic learning can be inferred in most of studies that do not detail the learning methodology but develop human joint robotic simulators, as robots are referred to as didactic tools for manual diagnosis or treatment (e.g. (Kong et al., 2021) or (Lee et al., 2020a, b)). Also, a hands-on learning is inferred from (Formosa et al., 2018) and (Pepley et al., 2016), as the robot goal is to simulate the environmental conditions faced when performing a colonoscopy or endoscopy, such as physiological properties or disturbances from patient movement. The same considerations can be extracted from (Zhou et al., 2004) and (Horvath et al., 2020), where the robots are respiratory motion simulators for performing radiosurgery and for correctly applying mechanical ventilators respectively.

On the other hand, visual learning is expected in (Chihara et al., 2013), where an expressive robotic head emulates the facial nervous system when performing facial expressions. The student is expected to gain skills in the diagnosis of cranial neuropathies through the visual examination of facial symptoms. The same approach appears in (Moosaei et al., 2017), where a robotic head simulates pain expressions to be recognized by the learner.

In (Hong et al., 2019) a hand-over-hand educational approach is proposed as an enhancement to passive haptic feedback simulators commonly employed in surgery education. Haptic feedback is given to the trainees based on the recordings of movements made by a specialized surgeon during surgery tasks. During training, the robot goes together with the trainee's hand and applies slight forces that simulate hand-over-hand guidance. A similar approach is shown in (Sharifi et al., 2016), where authors propose an additional variant based on a network-connected multiagent system for hemiparetic wrist of stroke patients' rehabilitation. Here the guiding force feedback can be averaged over a network of interconnected wrist rehabilitation devices, allowing different configurations with one or more instructors or patients in the robotic network.

Visual and auditory learning are employed in (Couto et al., 2017), where the Robot performs video lectures, encouraging speeches and examples for the education of intensive care unit worker professionals in hand hygiene practices. Also, in (Zubrycki et al., 2019) the robot is shown simulating an epilepsy seizure during educational workshops on epilepsy.

Robotic platforms are also employed either autonomously or remotely operated as the pathway to deliver the learning content and guide the educational process. For instance, in (Sampsel et al., 2014) instructor assists trainees in ICU tele-rounding through the use of a remotely controlled mobile robotic platform that accompanies them. In (Takanobu et al., 2007) and (Abe et al., 2018) the instructor evaluates the performance of dental students giving instructions to the patient robot via a PC interface, simulating a real study case through voice synthesis and patient behavior.

In (Lin et al., 2020) the robot autonomously guides and evaluates the learning process. By following a predefined checklist of steps for patient transfer procedures, voice commands and limb posture of the robotic patient can be used by nurses and students and to identify the steps to be executed during training. Meanwhile, the robot records its movements to provide feedback of the correctness of the procedure.

Robot acceptance

A small number of studies consider the acceptance of robots by the users. User acceptance is compiled by using questionnaires that include the acceptance of the technology (e.g. (Abe et al., 2018)), by qualitative description of observed effects (Couto et al., 2017) or by using discussion groups (Swain, 2017; Zubrycki et al., 2019). As extracted from the results, the overall acceptance by the participants is good, as the health students and professionals perceive them as useful tools for learning.

Discussion

To the best of the authors' knowledge, there is scarce literature focused on describing the factors affecting teaching–learning in health sciences education, apart from those focused-on training in the use of surgeon robots or surgeon robotic simulators. Given that robots are technological tools, we can follow a similar approach of other works that involve the use of technology to improve educational processes to analyze the obtained data. A recent systematic review on the factors affecting e-learning in health sciences education (Regmi & Jones, 2020) indicates as factor enablers: facilitate learning, learning in practice, systematic approach to learning and the integration of e-learning into curricula. As for factor barriers: poor motivation and expectation, resource-intensive, not suitable for all disciplines/ contents and lack of its skills. Similar enablers and barriers can be transposed to robotic technology in the discussion of the results found.

In terms of the enablers observed in our survey that coincide with those obtained by Regmi & Jones the following can be depicted:

Robots facilitate learning and quality assurance. Overall, results obtained from the analyzed papers seem to support this statement. For example, the results shown in (Sampsel et al., 2014), which studies the use of a remote telepresence robotic system in nursing education show that from 69 total respondents including faculty staff, clinical staff and 56 students, the majority (75%) felt that the robot was a good teaching/learning tool. In (Swain, 2017), they divided into two groups: one received training in CPR with and without the robotic simulator. Mixed methods (questionnaires and discussion groups were employed to determine if subjects were more comfortable in clinical setting after unexpected event using a robotic human patient simulator. Their results show that the robot helps transferring deeper tacit knowledge through experience and provide more effective training than explicit procedural learning.

Robots foster learning in practice. it can be seen from the analyzed studies that most of the work focus on kinesthetic learning, utilizing robots as hands-on practice didactic tools. Kinesthetic learning has long proven to be useful in medical training, for example in anatomy learning (Hernandez et al., 2020), as it provides four different effective learning modes: concrete experience, reflective observation, abstract conceptualization, and active experimentation (Kolb, 1983). In several of the works analyzed that describe users' judgement, there is a common opinion that robots are useful for learning in practice, as robots can faithfully reproduce real symptoms and simulate illness effects.

Robots allow a systematic approach to learning. The fact that robots allow to parameterize symptoms and reproduce them in a systematic way means that trainees can reliably repeat the same training, both in terms of patient-centric and procedure-centric approaches (e.g. (Lin et al., 2020)). Moreover, robots allow the inclusion of real patient data to emulate the physiological implications of a disease such as its severity in a systematic way (e.g. (Zakaria et al., 2014)).

As for the coinciding observed barriers, they include the following:

Poor motivation and expectation. Contrary to the results shown by (Regmi & Jones, 2020) in terms of e-learning, the use of other technology enhanced learning (TEL) in the health sciences field has proven to enrich and facilitate the transmission of didactic content, favoring medical training and motivating the students for example by using virtual or augmented reality (Escalada-Hernández et al., 2019; González Izard et al., 2020; Izard et al., 2018). However, when using robotic technology, the users' attitudes towards robots is a major concern, as robotic appearance and behavior influences and hinders their acceptance, especially when these robots resemble human beings (Müller et al., 2020; Savela et al., 2018). This important aspect of robotic technology is considered in few of the compiled studies. Further acceptance—focused research needs to be done to consider them as motivating, given that the questionnaires of the reviewed studies bias towards robot utility in pilot studies, and little towards user acceptance and long-term usage.

Robots may not be suitable for all disciplines/contents. This barrier can be inferred by the number of studies that coincide in the same health sciences field and robotic goals. It can be observed that most studies focus on diagnosis and treatment, while few focus on prevention. In addition, there is a dominant number of robots focused on modelling and simulating upper or lower limbs for physicians training. These results may come from the fact that traditionally robots have been built as industrial robotic arms as heavy objects manipulators to grasp and move objects in industrial environments. As such, most of the research done by robotic developers has focused on the study of the kinematic chain of robotic arms, which can be translated into the movement of joints present in human limbs.

Robots are resource intensive. Most of the studies in this systematic review use ad-hoc robotic constructions, which means that both their development process and their use and maintenance require specialized personnel. However, given the increasing development of commercial robotic platforms, the trend should be towards commercialization of specialized robotic constructions, with the consequent reduction in the cost of operation and maintenance. This evolution has already been observed both in surgical robots and in low-cost haptic simulators for training with these robots (Ginoya et al., 2021). There are some examples of using commercial components in the retrieved studies that diminish the development needed resources. For instance in (Couto et al., 2017) the low-cost humanoid robot MeccaNoid G15KS (Meccano Engineering & Robotics, n.d.) is employed. Or in (Sampsel et al., 2014), where a mobile platform is used endowed with the InTouch Health commercial software (Intouchhealth, n.d.).

The use of robots requires IT skills. Following the above discussion, ad-hoc constructions lead to the need for IT experts to manage them, which results in robots that do not evolve from piloted laboratory tests as is the case in most of the studies found. Even using commercial software, the need of IT skills is shown when evaluating the educational process (e.g. (Sampsel et al., 2014)).

Integration of robot-mediated learning into curricula. It is precisely in terms of integrating the activity developed with the robot into the training curricula that we observe the greatest hindering factor. This makes one of the enablers for health sciences e-learning described in (Regmi & Jones, 2020), to become a barrier when using robots. Contrary to what is happening in the field of robotic surgery, where there is a trend towards standardized validated curricula (Forgione & Guraya, 2017; Chen et al., 2020a, b; Khalafallah et al., 2020), the use of robots in other health sciences fields seems to be far from standardized.

The above-described barriers appear to be some of the causes for this delay. In addition, and maybe since the analyzed works are commonly developed by roboticists, it has been observed in most of the studies a lack of educational approach. For example, the training methodology is scarcely described nor is the target group specifically detailed. Even more, few studies make an explicit distinction regarding the adequate level of knowledge of the target group (e.g., student vs intern vs resident vs fellow vs attending). Our results seem consistent with those reported by (Nicoll et al., 2018), where they performed a systematic review of the literature relating to the evaluation of technology enhanced learning (TEL) programs for professionals in health sciences. As they described in their work, there continues to be a need to develop effective and standard TEL evaluation tools, and good quality studies that describe effective evaluation of TEL education for professionals in health sciences. Studies often fail to provide sufficient detail to support transferability or direct future TEL health care education programs.

Educational theories and learning processes that may facilitate the incorporation of robots in the teaching/learning process

As extracted from the previous discussion, different types of robots have different appearances and structures (hardware), software, and behavior. These features play an important role in determining the instructional activities and the learning objectives (Ferrada-Ferrada et al., 2020; Herrero, 2020). As these technological tools are usually developed from a roboticist perspective, they lack a common approach for their inclusion in the health sciences teaching/learning process. Applying well-established educational theories and learning processes could help overcoming the observed barriers.

In classical conditioning, for instance, a response to a stimulus is reinforced when it is followed by a positive reward effect. In this sense, major efforts should be put in endowing robots with user-friendly interfaces and interaction modalities (Camargo et al., 2021). On top of that, we observed few studies that considered user acceptance. Acceptance of robots by the users (students and teachers) should be further explored during and after robotic development, so to better adapt their design to users' expectations. Also, in classical conditioning a response to a stimulus will become stronger through exercise and repetition. This is provided by robots as they allow repetition of the same procedure. However, besides repeating general procedures or mimicking a joint movement, it may be important to endow robots with more "case-specific" capabilities, that foster problem-based learning by consistently simulating specific symptomatology of real patients as students will encounter when they practice.

Standardization of procedures when developing robots can reduce differences in their appearance and behavior. Following Ausubel's theory, using already developed and tested robotic components (e.g., using software already present in pcs) can help in reducing the need for IT skills, as learners will absorb new information by tying it to their existing knowledge. Also, employing user centered design principles and multimodal interaction that include human communication channels (i.e., voice or sound) can mitigate this barrier.

The use of robots beyond patient simulators should be promoted. For instance, fostering shadow learning as shown in (Sampsel et al., 2014), where they employ a mobile telepresence robotic system during nursing rounding. Results revealed that usefulness emerged in the areas of productivity, function, and observation, as participants felt that the robot facilitates course quality assurance when the lead faculty is not on site, and productivity was associated to the ability of the lead faculty to multitask.

In relation to the above and considering Bandura's social learning theory, it has been long demonstrated that prosocial robots elicit more prosocial behavior among users. Studies suggest that social responsive machines increase de acceptance of users towards them, as the feeling of affinity towards the machine reduces negative perceptual feedback. However, special care must be taken when developing a social robot, so to avoid falling into the uncanny valley if the user perceives a mismatch between robot's appearance and behavior (Cheetham, 2017). Moreover, cultural, age and gender differences should be taken into account when employing robots in health sciences education (for example, eastern cultures often rate lower levels of the uncanny valley than western cultures (Korn et al., 2021). Again, following user centered design principles and further analyzing the acceptance of robots by the users during the design process could help mitigating this effect.

From the above discussion, the case of (Lee et al., 2020a, b) is an example of how the development process for this type of robots should be approached. Instances of the same work (Murata et al., 2017; Lee et al., 2019a, 2019b; 2020b) show how the focus evolves from the mere robot design to the development of the control interface and automatic data capture and feedback that eases both the manipulation of the robot and a self-learning approach for students.

Limitations

As with any research procedure, there could be threats to its validity and limitations in the current systematic review. The first threat is that the inclusion of all the relevant studies in the field is not guaranteed. This threat was mitigated by piloting different searches, analyzing the retrieved results, and combining different databases. However, as can be depicted from the results, the number of papers that have reached the final stage after applying the quality criteria is quite low if compared with the number of papers retrieved from the search. To the best of the authors' knowledge, one of the main reasons is that the research field of robotic technology in the education of health professionals is not a consolidated field beyond surgery education, so scarce information can be retrieved. For that reason, the search scope was broadened to capture as much information as possible within the limits of the established review scope, and a methodology for screening has been followed. Another limitation arises by employing only the retrieved abstract for screening. As the abstracts of publications contain way less information than is contained in the full paper, this could lead to a bias in the search results.

Another limitation is that due to the scope of the studies that merge different fields (education, health, and robotics), most of the papers do not provide detailed descriptions for all the research questions. In addition, the identification of criteria for classification was not obvious in many cases, as many papers contained vague or fuzzy descriptions of the data to be extracted. For example, in terms of application-centric and system-centric robots there is a thin line in between determining if a robot is used to teach a procedure or if it is a system used to train the skills to handle a robotic tool. Furthermore, the boundary between what is and what is not a robot is a delicate one. To mitigate these effects, we tried to keep the review scope as concrete as possible, only considering robots those constructions that clearly showed together sensing, computing and acting capabilities with more or less degree of autonomy as described by the IEEE (What Is a Robot?, n.d.). The abovementioned threads were also mitigated by following a review protocol that involved both authors and tried to assure the quality of the obtained studies. Additionally, both researchers independently reviewed full texts during the process and discussed jointly to resolve uncertainties and reach consensus when necessary.

Finally, it must be noted that due to the review scope many papers devoted to surgery robots and haptic simulators have been discounted from the final review. In any case, given that there are several studies and surveys dedicated to the training of robots in surgery as well as to the study of haptic interfaces, the authors consider that this survey can be complementary to those studies.

Conclusion

This systematic review provides a broad overview of how robotics is integrated and considered in the health sciences education literature, beyond well-established surgical robots and system-centric approaches, by scoping the enablers and barriers that affect the use of robots as didactic tools for the education of professionals in health sciences.

Results show that, although there exist documented added-value benefits of the use of robots as didactic tools in medical education, further research on the issues found needs to be done to foster their inclusion in the curricula of health sciences professionals. On the one hand, by analyzing how robotic technology should be developed to become more flexible and usable to support both teaching and learning processes in health sciences education, as final users are not necessarily well-versed in how to use it. On the other, there continues to be a need to develop effective and standard robotic enhanced learning evaluation tools, as well good quality studies that describe effective evaluation of robotic enhanced education for professionals in health sciences. As happens with other technologies when applied to the health sciences field, studies often fail to provide sufficient detail to support transferability or direct future robotic health care education programs.

If robots in health sciences education are developed with a roboticist mindset, without clearly incorporating aspects of the learning process beyond development, they may remain as proofs of concept. Incorporating elements of learning may promote the potential for robots to improve parameterizing of results, autonomously guide learners to achieve greater engagement, and allow collective (multi-agent) learning including patients and instructors "in the loop".

Appendix 1

See Table 2.

Table 2 Piloted search strings

Database	Search string	No. results
WoS	(educators OR education OR teaching OR learning) AND (robots OR robotics OR robot) AND (medicine OR health OR care OR health sciences)	4837
	(education OR teaching OR learning) AND (robots OR robotics OR robot) AND (medicine OR health OR care OR health sciences)	4833
	(education OR teaching OR learning) AND (robotics OR robot) AND (medicine OR health OR care OR health sciences)	4833
	(education OR teaching OR learning) AND (robot*) AND (medicine OR health OR care OR health sciences)	4879
	(education OR teaching OR learning) AND (robot*) AND (medicine OR health* OR care)	5398
	(education OR teaching OR learning OR train* OR instruct*) AND (robot*) AND (medicine OR health* OR care*)	9219
	(education OR teaching OR learning OR train* OR instruct*) AND (robot* OR robotics OR robot) AND (medicine OR health* OR care*)	9220
	(education OR teaching OR learning OR train* OR instruct*) AND (robot*) AND (medicine OR health* OR care* OR therapy OR treatment)	12,703
	(education OR teach* OR learn* OR train* OR instruct*) AND (robot*) AND (medicine OR health* OR care* OR therapy OR treatment)	12,739
	(education OR teach* OR learn* OR train* OR instruct*) NEAR/2 (medicine OR health* OR care* OR therapy OR treatment) AND (robot*)	808
	(education OR teach* OR learn* OR train* OR instruct*) NEAR/3 (medicine OR health* OR care* OR therapy OR treatment) AND (robot*)	1061
	(education OR teach* OR learn* OR train* OR instruct*) NEAR/4 (medicine OR health* OR care* OR therapy OR treatment) AND (robot*)	1309

Table 2 (continued)

Database	Search string	No. results
Scopus	(educators OR education OR teaching OR learning) AND (robots OR robotics OR robot) AND (medicine OR health OR care OR health sciences)	503
	(education OR teaching OR learning) AND (robots OR robotics OR robot) AND (medicine OR health OR care OR health sciences)	501
	(education OR teaching OR learning) AND (robotics OR robot) AND (medicine OR health OR care OR health sciences)	501
	(education OR teaching OR learning) AND (robot*) AND (medicine OR health OR care OR health sciences)	506
	(education OR teaching OR learning) AND (robot*) AND (medicine OR health* OR care)	4966
	(education OR teaching OR learning OR train* OR instruct*) AND (robot*) AND (medicine OR health* OR care*)	8878
	(education OR teaching OR learning OR train* OR instruct*) AND (robot* OR robotics OR robot) AND (medicine OR health* OR care*)	8878
	(education OR teaching OR learning OR train* OR instruct*) AND (robot*) AND (medicine OR health* OR care* OR therapy OR treatment)	12,852
	(education OR teach* OR learn* OR train* OR instruct*) AND (robot*) AND (medicine OR health* OR care* OR therapy OR treatment)	13,332
	(education OR teach* OR learn* OR train* OR instruct*) W/2 (medicine OR health* OR care* OR therapy OR treatment) AND (robot*)	1098
	(education OR teach* OR learn* OR train* OR instruct*) W/3 (medicine OR health* OR care* OR therapy OR treatment) AND (robot*)	1425
	(education OR teach* OR learn* OR train* OR instruct*) W/4 (medicine OR health* OR care* OR therapy OR treatment) AND (robot*)	1728

Appendix 2

See Table 3

Table 3 Considered studies and summary of extracted data

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Kong et al., 2021)	Upper-limb simulator	Physical therapists / physiotherapy	Diagnosis: manual diagnosis of muscle spasticity Treatment: manual rehabilitation	Patient centric	Case specific: spasticity	Justificative—experts group vs Trainee group. (n = not specified)	Compares trainees vs experts educational effects on repetitive training	Not detailed	No
(Lee et al., 2020a; , b)	Upper-limb simulator	Nurses & therapists / elderly care	Prevention – treatment: passive range of motion (rom) exercises	Patient centric	General/case specific: elderly shoulder	Justificative – (n = 5) experts	Differences in quantitative captured data among the experts after completing 3 exercises (Elevation–depression, extension-flexion, lateral rotation-medial rotation)	Not detailed	**No**

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Ishikawa et al., 2015)	Wearable robotic knee joint as impairment simulator	Physical therapists / physiotherapy	Diagnosis: manual diagnosis of five different knee joint symptoms	Patient centric	Case specific: five types of simulated symptoms: lead-pipe rigidity, cogwheel rigidity, spasticity, limitation of motion range (contracture), limitation of motion range (bony ankylosis)	Descriptive—(n = 8) experienced clinicians	Rated the 5 simulated symptoms: how well the simulator presents different severities of the disease & how well the simulator models symptoms	Not detailed	No
(Zakaria et al., 2014)	Upper-limb simulator	Physical therapists / physiotherapy	Treatment: manual rehabilitation	Patient centric	Case specific: three types of simulated symptoms: Lead-pipe rigidity, Cogwheel rigidity, Spasticity, obtained from real patient's data	Descriptive—(n = 2) experienced clinicians	Two experienced clinicians evaluate the symptoms and severity. Results compared against real patient data	Not detailed	No

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Maeda et al., 2012)	Knee joint simulator	Physical therapists / physiotherapy	Treatment: manual rehabilitation	Patient centric	Case specific: clonus and hypertonia	Descriptive – (n = 1)	One experienced clinician evaluates the reproduction of hypertonia. Compares feeling sensation between robot and real patient	Not detailed	No
(Sampsel et al., 2014)	Teleoperated mobile robotic platform controlled by instructor	Nursery	Prevention / treatment: ICU tele-rounding	Application centric	Procedure: tele-rounding in Intensive Care Unit in a simulated multigenerational home	Clarificatory—Seventy students (n = 70) and five (n = 5) faculty members	Questionnaires, provided feedback on the didactic interaction: usefulness, acceptability, impact	Instructor assists trainees in ICU tele-rounding through the mobile platform	Yes
(Couto et al., 2017)	Humanoid Robot	Intensive Care Unit workers	Prevention: education of health professionals in hand hygiene practices	Application centric	Basic task: hand hygiene	Justificative—(n not specified)	Percentage rates of hand hygiene compliance rates in three ICUs with and without robotic education	Robot performs video lectures, encouraging speeches and examples	Partial—qualitative description of observed effects

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Othman et al., 2018)	Upper -limb (elbow) simulator	Physical therapists / physiotherapy	Diagnosis: manual diagnosis	Patient centric	Case specific: spasticity	Descriptive – (n = 1)	One experienced clinician evaluates the reproduction of hypertonia. Compares feeling sensation between robot and real patient	Not detailed	No
(Sharifi et al., 2016)	Multirobot network. Each simulates wrist's joint movements	Physical therapists / physiotherapy	Treatment: robotic rehabilitation	Application centric	Procedure: hemiparetic wrist of stroke patients' rehabilitation	Descriptive – (n = 1)	Performance of the patient after 60 days of stroke recovery (Not evaluated over trainees)	Force Feedback model applied to trainees based on learned movements from therapist over real patient, therapist over robot, and averaged over a multirobot system	No

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Swain, 2017)	Human patient robotic simulator (HPS) (not described)	Nurse students / Nursery	Treatment: intervention in cardio-pulmonary resuscitation (CPR) emergency	Application centric	Procedure: CPR	Clarificatory—(n = 7)	Divided into two groups: one received training in CPR with and without the robotic simulator. Mixed methods (questionnaires and discussion groups) to determine if subjects were more comfortable in clinical setting after unexpected event using a (HPS)	Training CPR with a HPS robot that simulates cardiopulmonary failure	Yes

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Hakogi et al., 2005)	Knee joint robot simulator	Physical therapists / physiotherapy	Treatment: knee joint rehabilitation	Patient centric	General: anatomy/physiology	Descriptive	Compare robot quantitative dynamic torque with measured data during clinical rehabilitation treatment	Not detailed	No
(Formosa et al., 2018)	Actuated robotic platform to fit a synthetic colon. Simulates peristaltic wave speeds and pressures, and disturbances from patient movement	Doctor / gastroenterologist	Prevention – diagnosis: endoscopy—colonoscopy	Patient centric	General: anatomy/physiology	Descriptive	Compare robot quantitative dynamic deformations and displacements with measured data in clinical settings	Not detailed	No

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Zhou et al., 2004)	Respiratory motion simulator (2 independent platforms): skin-motion and tumor-motion simulators	Surgeons / radiosurgery	Treatment: radiosurgery accuracy	Patient centric	General / case specific: anatomy/physiology Case specific: respiratory tumor	Descriptive	Compare simulated sinusoidal waves and human respiratory motion with measured data in clinical settings	Not detailed	No
(Horvath et al., 2020)	Respiratory motion simulator. Simulates lung, the abdominal cavity, pleural cavity	Doctors – nurses / Intensive Care Unit	Treatment: mechanical ventilation	Patient centric	General / case specific: anatomy/physiology	Descriptive	Compare the compliance of different elements with measured data in clinical settings. Integration with mechanical ventilators in tailored learning. Allows testing different ventilation modes	Not detailed	No

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Takanobu et al., 2007)	Human-like robot simulator. Full body joint movements, facial expressions, eye tracking & mouth movements. Sensorized mouth leading to a vomiting reflex and pain during teeth drilling. Voice recognition. Blood effusion	Dentists—dental nurses / Dentistry	Treatment: teeth drilling	Application centric Patient centric	Procedure: diverse dental procedures General anatomy/ physiology Case Specific: patient behavior	Justificative—(n = 29) students,	Evaluated with (n = 29) students, grouped in trainee and assistant. Cavity preparation and drilling of back molars. Students respond a questionnaire on robot behavior, usefulness and acceptance after training	Supervisor evaluates the performance of students giving instructions to the patient robot via PC interface	Yes
(Pepley et al., 2016)	Rotational and translational robotic gastrointestinal endoscopy simulator	Colonoscopy	Diagnosis – prevention: endoscopy	Application centric	Procedure: colonoscopy, upper GI (gastrointestinal) endoscopy & endoscopic retrograde cholangiopancreatography	Descriptive	Compare experimental results of the force bandwidth with measured data in clinical settings and other simulators	Not detailed	No

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Wang et al., 2015)	Elbow joint simulator. Simulate the symptoms of motor nerve system	Neurological elbow examination	Diagnosis: neurological examination, muscle force, reflex action, tremor	Patient centric	Case Specific: lead-pipe rigidity	Justificative – (n = 3) experienced doctors	Questionnaire survey by expert doctors after elbow examination (muscle tension, biceps tendon reflex, involuntary action). Evaluated teaching effectiveness: for student, for trainee, for expert and—if better than standard teaching	Not detailed	Yes

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Lin et al., 2020)	Full body robot patient simulator. Simulates and measures all body joints	Nurses / correct transfer skills of patients	Prevention: prevent errors and harming patient during transfer	Application centric	Procedure: correct transfer of patients to and from wheelchairs	Justificative – (n = 4) experienced nursing teachers	Statistical analysis produced 8 parameters to be evaluated during patient transfer (e.g. Rotational speed of the chest). Evaluated if significant statistical difference exists between the correct and incorrect methods for the 8 parameters	Voice commands and limb posture of the robot patient used by the nurse to identify the steps being executed during training	No
(Park et al., 2012)	Elbow joint simulator	Physical therapists / physiotherapy	Diagnosis: manual diagnosis of muscle spasticity	Patient centric	Case specific: spasticity	Justificative – (n = 8) experienced clinicians	Evaluated 4 real patients, 4 simulations of those models and 4 randomly generated simulations	Not detailed	No

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Chihara et al., 2013)	Realistic facial robot with expressiveness. Emulates facial nervous system	Neurological facial examination / neurologists	Diagnosis: cranial nerve diseases and symptoms	Application centric	Procedure: visual cranial nerve examination of eyeballs and skin wrinkles	Justificative – (n = 4) experienced neurologists	Assessment of eyeball movements	Not detailed	No
(Abe et al., 2018)	Human-like robot simulator. Full body joint movements, facial expressions. Body and mouth sensors. Voice synthesis	Dentists—dental nurses / Dentistry	Treatment: diverse dental procedures	Application centric Patient centric	Procedure: diverse dental procedures General anatomy/ physiology	Justificative – (n = 10) undergraduate dental students	Comparison of robotic simulator vs mannequin. Mixed methods. elapsed time for crown preparation on an upper pre-molar tooth. Measured taper of the abutment teeth. Questionnaires on physical pain, treatment safety and maintaining a clean area	Instructor operates GUI software to act as an intermediary between the students and the robot patient while considering a natural scenario	Yes – text mining analysis of open questions

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Zubrycki et al., 2019)	Robotized full-body mannequin simulates an epileptic seizure	Medical nurses and paramedics	Treatment	Application centric	Procedure: protocol when epileptic seizure	Justificative – (n = not specified)	Pre and post workshop questionnaires regarding knowledge about epilepsy. Statistical analysis between epilepsy workshops with educational movies and with the robot	Educational workshops on epilepsy	Yes- participatory discussions
(Frey et al., 2006)	Human mannequin with hip and knee joint simulator. Voice pain indicator	Physical therapists / physiotherapy	Diagnosis: manual diagnosis different knee joint symptoms	Application centric	Procedure: examination of a knee joint	Justificative –(n = 24) nonmedical (n = 12) orthopedic	Questionnaire to compare haptic feelings with real human leg vs robotic leg. Nonmedical answers used as control group	Not detailed	Yes—questionnaire

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Hong et al., 2019)	Robot manipulator for kinesthetic learning in surgical procedure	Surgeons / Surgery	Treatment: surgical procedures	Application centric	Basic task: Surgical tasks	Justificative – control vs experimental group of novices (n = not specified)	Trainer records a trajectory. Control group conducted the task without guidance while the experimental group carried out the task with guidance	'hand-over-hand' learning. Records the motion of a senior surgeon doing a specific surgical task, and reproduces the track during training + visual and vocal guidance	No

Table 3 (continued)

Source	Robot Description	Target Group / Health Sciences Field	Teaching/training goals	Modelling category	Modelling level	Research type	Evaluation method	Teaching / learning process	Acceptance
(Moosaei et al., 2017)	Facially Expressive Robot that simulates pain expressions	Clinicians	Diagnosis—prevention: clinical Pain Perception	Application centric	Basic task: detect pain in patient simulators	Clarificatory – (n = 51) clinicians (n = 102) laypersons	Video – based study on accuracy in pain perception and embodiment (robot vs. avatar). Clinicians show lower overall accuracy in detecting synthesized pain. Also lower accuracy in robotic vs avatar faces	Not detailed	No
(Okumura et al., 2013)	Wearable and adjustable robot that constraints foot in various equinovarus positions	Physical therapists / physiotherapy	Diagnosis: manual diagnosis of equinovarus	Patient centric	Case specific: equinovarus	Descriptive—(n = 5) experienced clinicians	Manual examinations of a healthy person wearing the robot. Compare feeling sensation between robot and real patient	Not detailed	No

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Authors and Affiliations

Samuel Marcos-Pablos[1] · Francisco José García-Peñalvo[1]

✉ Samuel Marcos-Pablos
samuelmp@usal.es

Francisco José García-Peñalvo
fgarcia@usal.es

[1] GRIAL Research Group, University of Salamanca, IUCE, Paseo de Canalejas 169, 37008 Salamanca, Spain