Robotics Technology for Pain Treatment and Management: A Review

Angela Higgins[1], Alison Llewellyn[2], Emma Dures[2], and Praminda Caleb-Solly[1]

[1] School of Computer Science, University of Nottingham, NG8 1BB
[2] Faculty of Health and Applied Sciences, UWE, BS16 1QY, UK
angela.higgins@nottingham.ac.uk

Abstract. The use of robots for pain management is a new and active research field. The aim of this scoping review is to identify current research, which groups or conditions are being targeted for treatment, which devices are being used, and how effective they have been. Using the PRISMA protocol for scoping reviews, papers were identified using university libraries, Google scholar and additional databases relating to healthcare or engineering including AMED, NICE Evidence, and OT-Seeker. Included were articles involved user trials of a robot or device to manage or alleviate pain, with a quantitative measure of pain or pain anxiety. 17 articles were analysed, of which 12 reported statistically significant improvement of pain measures. The scope and trial design of these articles varied widely. Most devices used were socially assistive robots, with others using robots for physical therapy. Most robots were used for treatment of procedural pain. Others addressed chronic pain, particularly in people with dementia. A variety of established pain measurement techniques were used to quantify difference in perceived pain or pain anxiety. There may be benefits to using some robotic technologies to manage pain for both acute and chronic pain conditions, within certain populations. However, this research field is still new, and more studies are required to demonstrate efficacy. Future studies should look to use methodologies from clinical trials to improve the quality of their results.

Keywords: pain, pain management, robotics, socially assistive robots

1 Introduction

During our lifetimes we will all experience pain, whether acute and short-term or chronic and long-term. Both acute and chronic pain can be life restricting, due to temporary anxiety around pain or ongoing debilitation. Chronic pain persists or recurs for more than 3 months [45], and it can be a disease in itself or a symptom of another condition. Acute pain has a duration of less than 3 months, reduces over time, and usually occurs as the result of a singular incidence of trauma, such as an accident or medical procedure [39].

Due to increasing awareness of potential disadvantages of pharmacological treatments, many researchers are seeking to find non-pharmacological and non-surgical interventions that may help alleviate pain. This scoping review aims to evaluate contemporary research into the use of robotics technologies for pain alleviation or management, including both acute and chronic pain.

Currently, simple electronic devices are sometimes used in medical settings to help those living with pain. These include transcutaneous electrical nerve stimulation (TENS) machines and vibrotactile devices [44]. Additionally, the use of virtual reality (VR) for distraction and relaxation has shown potential for pain alleviation [14]. Other research has combined haptic and VR technology to create multimodal pain alleviation, with some positive outcomes [27]. Whilst these are technologies often linked to robotics, no robots were used in these prior studies therefore they are beyond the scope of this review.

Chronic pain treatment is complex and multifaceted, and the application of technology to aid in self-management at home may benefit pain patients by assisting with daily routines, providing soothing sensations or mimicking physical therapy (PT) [23]. Additionally, those experiencing acute pain in a medical setting, such as a painful procedure, may benefit from technological methods that lessen pain and lead to better outcomes [19]. Generally interventions use one of three existing theoretical approaches to pain management: pain distraction, pain gating or cutaneous stimulation, and affective touch, described below.

Distraction as pain management works by shifting the individual's attention from the painful sensations and onto another stimulus. This includes methods such as visualisation exercises or engaging in an enjoyable hobby. It can also be beneficial during shorter painful medical procedures, however the type of distraction should be adjusted according to patient and procedure [22].

The gate control theory of pain, whilst contested, has been used in the development of pain management techniques currently in use. The theory states that pain signals travelling along the nervous system to the brain can be interrupted at the spinal cord by the generation of other signals [12]. An example of this used in medical settings is TENS machines to reduce pain associated with childbirth, although their efficacy is disputed [6].

Similar to pain gating, in that it involves physical stimulation of the body, cutaneous stimulation involves using tactile stimuli often on or near the pain site [18, 15]. However, whilst pain gating seeks to reroute the electrical signals travelling to the brain, cutaneous stimulation seeks to lessen pain sensations by overriding them with pleasant stimuli.

Robotics technologies have already been imagined, researched and deployed in a variety of healthcare scenarios, and it is hoped that robotics will become integrated into a patient's healthcare journey [28]. Even more recently researchers have become interested in the potential for robots to be used in pain alleviation or management. As with other technologies, it may be that robots can be used as alternative or complementary interventions for pain management.

Frequently, pain management research uses a socially assistive robot (SAR), that provides assistance through social interaction including dialogue, sounds and gestures, rather than providing physical assistance [17]. This utilises human-robot interaction (HRI) to distract or relax a patient undergoing a procedure or therapeutic regimen. Research into SARs and HRI has already shown potential uses in healthcare, particularly the care of people in later life, providing assistance, therapy or comfort and improving quality of life [1]. However, sometimes this involves a robot that has no social features designed to interact with the body as part of physical therapy. This scoping review looked for current research into robotic treatments of pain in order to identify trends such as groups and conditions targeted for treatment, devices used and their effectiveness. From this possible recommendations were made for future research.

2 Methods

2.1 Search Methods

The aims of this review were to identify and analyse research which indicates how robots could possibly be used to alleviate or manage pain. This scoping review sought to answer the following research questions:

(i) What research currently exists into the use of robots or robotic devices for pain alleviation and/or management?
(ii) Which groups or conditions are being considered for the potential use of robots for pain alleviation and/or management, and in what form?
(iii) Which robots or robotic devices have shown efficacy for the alleviation and/or management of pain?
(iv) Based on the findings from current research what recommendations can be made for future research?

2.2 The PRISMA Protocol and Search Strategy

Methods from the PRISMA protocol for scoping reviews were used as the search strategy [42]. This involved searching the library database at the University of the West of England, Google Scholar and additional databases relating to healthcare or engineering. Additional records were sourced through Altmetric and cited references in publications. Searches were performed between October 2019 to March 2022 inclusive. The initial search was broad, and all possibly relevant articles were included based on screening of titles, abstracts and references. The inclusion criteria were literature written in English and published between 2000 to spring 2022. However due to the active nature of the research topic no results were found prior to 2010. Search terms are shown in Table 1, where each word from the first column was combined with each word in the second.

2.3 Selection Criteria

Full length articles were included if they contained user trials using a robot or a robotic device, and used a quantitative measurement of pain or perceived pain, including those that used anxiety questionnaires with specific reference to pain. The PRISMA flow diagram is shown in Figure 1. A robotic device was defined as an interactive device which has an embodied presence. This excluded articles discussing pain treatment methods such as vibration or TENS machines, or those using virtual reality for pain treatment. Duplicate results were also removed, as well as studies which used the same experiments for more than one publication. Results are shown in Table 2.

Table 1: Search Terms

First term	Second term
robot	pain
robotics	pain relief
socially assistive robot	pain management
Paro	pain therapy
NAO	pain distraction
assistive robot	analgesia
assistive technology	analgesic

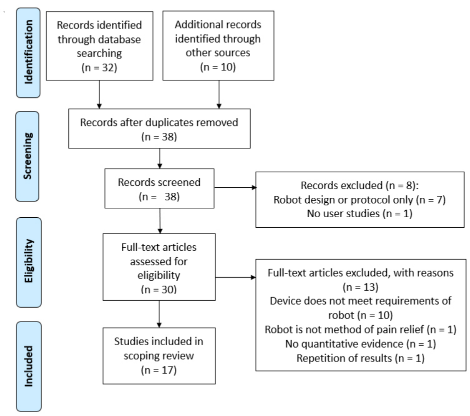

Fig. 1: PRISMA Flow Diagram

3 Results

3.1 Demographics and Study Design

The search elicited 17 articles, within which participant groups, trial design, type of measurements and study duration varied widely. Articles originated from 8 countries and study locations included clinical settings, such as a hospital or doctor's office (n=14), long-term care facilities (n=3) and a university laboratory (n=1). All articles were published after October 2012, with an increasing amount occurring in subsequent years until the end of the search period.

Participants in user trials were usually members of a specific patient population, for example paediatric patients, from premature infants up to 18 years, plus one study that classified children as up to 19 years (n=11, total 462 participants). These children were in treatment for long-term medical conditions such as cancer or undergoing an isolated medical procedure, often as part as a long-term treatment program. The largest study involving children examined 86 patients undergoing IV insertion, and the smallest examined 10 premature infants (born at less than 36 weeks of gestation) undergoing a blood test.

Other notable participant groups were: people with dementia (n=3, total 79 participants); and people receiving post-stroke rehabilitation (n=2, total 73 participants). Finally, one group contained healthy adults who were subject to experimentally induced pain (n=1, total 83 participants).

Most participant groups were randomly split into intervention and control groups for comparison, with one article using sample stratification for gender. The remainder compared each patient's results and relative improvement over time. Most studies were non blinded, however 3 used blinded analysts to review

Table 1: Results

Authors, Year, Country	Robot	Participants	Pain Condition	Measurements	Technique	Sig. Results
Alemi et al. 2016, Iran [2]	NAO	11 children (7-12yrs)	Cancer	MASC scale	Talk therapy	Yes
Ali et al, 2021, Canada [3]	NAO	86 children (6-11yrs)	IV insertion procedure	FPS-R and OSBD-R	Distraction	Yes
Ariji et al. 2015, Japan[4]	Oral therapy robot	37 adults (19-83yrs)	Myofascial pain	VAS and max mouth opening	PT	Yes
Beraldo et al. 2019, Italy [7]	Pepper and Sanbot	28 children (3-19yrs)	Various medical procedures	Self-designed questionnaire	Distraction	Yes
Beran et al. 2013, Canada[8]	NAO	57 children (4-9yrs)	Vaccination procedure	FPS-R and BAADS	Distraction	Yes
Borboni et al. 2017, Italy [9]	PT robot	25 adults (45-80yrs)	Post-stroke rehab	VAS	PT	Yes
Farrier et al. 2019, Canada [16]	NAO	46 children (2-15yrs)	IV insertion procedure	FPS-R + CFS	Distraction	Yes
Geva et al. 2020, Israel [20]	Paro	83 adults (M=25.1yrs)	Experimentally induced	VAS and salivary oxytocin	Affective touch	Yes
Holsti et al. 2019, Canada [25]	Calmer	49 premature infants	Blood test	BIIP and heart rate	Affective touch	No
Jibb et al. 2018, Canada [26]	NAO	40 children (4-9yrs)	IV insertion	FPS-R and BAADS	Distraction	No
Kim et al. 2019, Korea [29]	PT robot	38 adults	Post-stroke rehab	VAS and range of motion	PT	Yes
Lane et al. 2016,USA [30]	Paro	23 adults (58-97yrs)	Dementia related	Carer assesed	Affective touch	No
Manaloor et al. 2019, Canada[32]	NAO	86 children (6-11yrs)	IV insertion procedure	FPS-R and OSBD-R	Distraction	Yes
Okita 2013, USA[34]	Paro	18 children (6-16yrs)	Various medical procedures	FPR-S and anxiety questionnaire	Affective Touch	Yes
Pu et al. 2020, Australia [36]	Paro	11 adults (65-94yrs)	Dementia related	COREQ compliant questionnaire	Affective Touch	Yes
Trost et al. 2020, USA [43]	MAKI	31 children (4-14yrs)	IV insertion procedure	FPS-R and CFS	Distraction	No
Williams et al. 2019, Canada [46]	Calmer	10 premature infants	Blood test	Heart rate	Affective touch	Yes

and encode data after the studies. All articles used at least one standardised qualitative measurement of pain, or questionnaires adherent to the COREQ checklist for qualitative research [41].

3.2 Types of Robots

The majority of articles used commercially available SARs, particularly the small humanoid robot NAO (n=6) and the baby seal robot Paro (n=4). Others SARs used included the Maki and the humanoid robots Pepper and Sanbot. The most common experimental robot-participant combination was NAO for pain management in children (n= 6) and Paro for people with dementia (n=2). These robots and their frequency of use are shown in Figure 2.

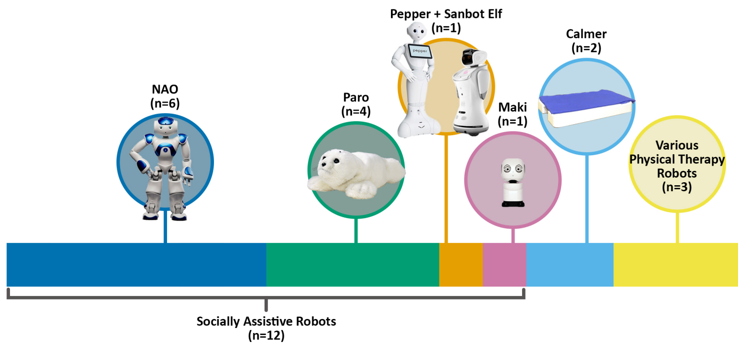

Fig. 2: Robots Used in Studies

3.3 Pain Conditions

A number of articles observed the treatment of procedural pain (n=8), including intravenous insertion (n=4), needles (n=2) and other one-off medical procedures (n=3). These medical procedures are brief but common; most people will undergo them at least once during a lifetime.

Other studies were used to treat chronic pain associated with dementia (n=2) or acute pain associated with ageing in people with dementia (n=1). Others aimed to mimic physical therapy for specific long-term conditions (n=3).

In some articles procedural and experimental pain management only lasted for the duration of a singular medical treatment (n=10), whereas other pain management interventions consisted of a regular therapeutic program (n=6), for example once a week over a number of months. One trial with people with dementia had no specific protocol for robot use, employing Paro as and when medical staff thought it appropriate.

Several robots were used to recreate physical therapy (n=3) to help alleviate pain in a specific condition, through therapeutic methods employing massage or joint manipulation. These robots are usually designed to mimic procedures performed a therapy professional, with the aim to provide more frequent therapy and assist recovery.

The Calmer robot, used in two studies, simulates parental warmth, breathing and heartbeat. This was used with premature babies to mimic skin-to-skin contact which is used to soothe infants during medical procedures. The device has the appearance of a small bed which the baby is placed upon with to create calming sensations.

3.4 Pain Management and Techniques

The majority of articles (n=13) reported a statistically significant improvement in perceived pain or pain anxiety post intervention ($p<0.05$). Although in those studies without significant positive effect no difference was found between current standard interventions or those using robots. All articles reviewed gave details of the techniques they employed to manage user pain. These techniques are underpinned by existing theoretical work into pain management and techniques already in use, including medical professionals and therapeutic animals. In the articles reviewed, these theories and protocols were implemented through the use of robots for the specific purpose of investigation.

One of the most common methods to manage pain using robots was distraction (n=7), often using NAO performing a routine. SARs were pre-programmed or operator-controlled to provide interactions that included performing for the child, to put attention on the robot and away from the procedure at hand. One study used NAO to implement talk therapy to increase understanding and decrease distress and associated pain. The robot interacted with children allowing them to speak about their pain and anxiety.

Other articles applied cutaneous stimulation, using comforting tactile stimuli (n=6). Paro, as a soft and tactile robot, was often used to deliver therapeutic touch as a substitution for pet therapy, particularly for people with dementia. A notable exception using cutaneous stimulation was the use of the Calmer robotic device to mimic affective touch of a parent.

3.5 Pain Measurement

Pain itself can be difficult to measure, as one person's perceptions and tolerance can be different from the next [13]. Frequent measurements of pain included the self-reported Wong-Baker FACES pain rating scale or Faces Pain Scale – Revised (FSP-R) [24]. Alternative self-report measurements included the visual analogue scale (VAS) for pain [31]. Others used self-reported measurements relating to pain anxiety or behaviours such as the Multidimensional Anxiety Scale for Children (MASC) [33] or their own interviews or questionnaires.

Researchers also used observation and behavioural assessment including Behavioral Approach-Avoidance Distress Scale (BAADS), Children's Fear Scale, Observational Scale of Behavioral Distress – Revised (OSBD-R), Pain Assessment in Advanced Dementia (PAINAD) or observation by trained carers. These measures could be complementary to self-reporting or useful when self-reporting was not appropriate.

Self-report and observational measurements, however, have limitations and can be prone to bias. To complement these measurements some studies therefore used physiological measurements including heart rate and salivary oxytocin, a hormone linked to reduced pain sensitivity and anxiety [37]. In the case of preterm infants, who evidently are unable to self-report, only one physiological measurement, in the form of heart rate, was used. Additionally, for robots treating a particular physical condition, such as post-stroke rehabilitation, improvements in qualities such as range of motion could also be measured. The nature of the scales is summarised in Table 3.

4 Discussion

Research into potential pain interventions using robots is ongoing, and interest in the area is increasing as robots are implemented for new healthcare applications. Early research indicates some positive results for the use of robots for pain treatment, with 13 out of 17 studies reporting statistically significant improvement in quantitative measurements of pain or pain anxiety. However, more studies are needed to prove efficacy.

All included articles based their interventions on existing theories of pain management, including pain distraction, cutaneous stimulation and physical therapy. Further research should investigate which methods of pain management are beneficial for different user groups and conditions. Some methods may be more appropriate in different situations, particularly when it comes to procedural (distraction) as opposed to long term (therapeutic) pain.

Several articles investigated treatment of chronic pain, particularly with people with dementia. Here complementary pain management could prove particularly beneficial, and affective touch may have additional benefits for this population [21]. Other articles concerned the use of distraction for young people undergoing acutely painful medical procedures, like those currently used by medical professionals. Additionally, some robots were used to mimic physical therapies for conditions that require long-term treatment with a human therapist.

A benefit of using social robots and human-robot interaction for pain management is that human-human interaction techniques can be replicated. For example, NAO often performed a routine designed to engage a child and distract them from a medical procedure. The baby seal robot Paro was often used as a replacement for pet therapy which is used in dementia care. Compared to humans or animals, robots are able to provide a more consistent and controlled intervention.

Commercially available socially assistive robots were used in the majority of studies and often demonstrated some efficacy at reducing pain or anxiety

Table 2: Pain Measurements

Abbrev.	Self-Report	Observation	Physiology
BAADS		x	
BIIP		x	
CFS	x		
FPS-R	x		
Heart Rate			x
MASC	x		
PAINAD		x	
Salivary Oxytocin			x
VAS	x		

in those using them. However, these toy-like robots may also indicate a level of infantilisation, particularly when children and people with dementia are the primary study groups. The use of commercial robots could also be considered techno-centric, with existing technology reflectively applied to pain management. It may be beneficial for researchers to consider co-design of robots or interventions alongside stakeholders, particularly when therapeutic treatment may need to be flexible and customisable [47]. Additionally, little mention was made regarding the acceptability or suitability of the robots for pain management from end users, which may improve both uptake and outcomes [35].

Trialing non-pharmacological treatments for pain can be difficult, but future research should consider established protocols, for example, the Stage Model of Behavioural Therapies [38] which has also been adapted specifically to new chronic pain therapies [11]. This guide uses three stages before an intervention can be considered effective, and all articles in this review would be considered at stage 1a (Therapy Design/Manual Writing) or 1b (Pilot and Feasibility Testing).

Furthermore, most articles failed to report detailed demographic information. Participants were often allocated to control or intervention groups randomly, with only one using stratified sampling based on gender. Whilst this is not always necessary, existing research has shown the acceptance of robots varies dependant on factors including age, gender and cultural background [5, 10] as well as the task the robot is to perform [40].

Pain is a subjective, personal and lived experience; therefore, it is difficult to quantify the pain a person is feeling. Most studies used well-known methods for self-reporting combined with behavioural observations. Some combined these scales with biometric measurements, providing bodily responses to pain, which may be more reliable as self-report can be tracked alongside physiological outcomes. Finally, there may be some benefit to measuring more long-term quality of life indicators associated with pain for those living with chronic conditions.

The limitations of this review and the included articles are primarily due to emerging nature of the research topic. Whilst positive outcomes have been demonstrated studies are often small and require more rigorous measurements to quantify their results. Future research should look to expand upon initial positive results and investigate why these methods are successful, whilst looking to investigate other patient groups and methods of intervention design.

5 Conclusion

Initial research shows potential for using robots to manage or alleviate pain, however more research is needed to show efficacy. Interventions using robots often use existing theoretical framework for the treatment of pain. Commercially available social robots were used most frequently, for the treatment of children or people with dementia. Further research should look at the appropriateness of different treatment types for different user groups and seek to design interventions based on the needs of these groups. Existing research has demonstrated the need for robots to be appropriate for a user group and task to be effective, so this should also be considered. Further trials should look to models of non-pharmacological clinical trials to ensure the effectiveness of using robots for pain management. Expanded research with more user groups and different intervention approaches should be conducted with more formalised methodology to better explore the potential for robots to be used for pain alleviation or management.

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