Informatics in Medicine Unlocked 18 (2020) 100298

Contents lists available at ScienceDirect

Informatics in Medicine Unlocked

journal homepage: http://www.elsevier.com/locate/imu

The Internet of Things (IoT) in pain assessment and management: An overview

Erick Javier Argüello Prada

Facultad de Ingenierías, Departamento de Tecnologías de la Información y las Comunicaciones, Universidad Santiago de Cali, Calle 5 # 62-00 Barrio Pampalinda, Santiago de Cali, Colombia

ARTICLE INFO

Keywords:
Embedded technologies
Health
Internet of things (IoT)
Pain assessment
Real-time monitoring

ABSTRACT

Potential benefits and risks of the application of the Internet of Things (IoT) in the healthcare domain have already been analyzed. Nevertheless, the role that IoT has played to date regarding the assessment or management of pain remains unexamined. The present study aims to fill this gap by providing a comprehensive review of the application of the IoT in pain assessment and management. A literature search (2000–2018) was conducted in five electronic databases pertaining to medical and engineering literature, in order to cover both technological and clinical aspects of the research topic. Article selection was done through a process of removing duplicates and excluding articles that did not meet the inclusion criteria. After reviewing the full text of the remaining articles, only sixteen publications were included for analysis. All the selected studies describe the use of one or more IoT-enabling technologies for pain assessment, but only a few illustrate the implementation of such technologies for pain management. Moreover, IoT-enabling technologies have been mostly used in isolation rather than combined under the IoT philosophy, and barriers impeding the adoption of IoT-based solutions for pain assessment and/management include the difficulties involved in pain assessment itself and the lack of a pain assessment culture, as well as security and privacy issues. Further development of this field depends on effective collaboration between engineers and healthcare providers.

1. Introduction

Pain is one of the most common reasons why individuals seek medical attention and it continues to be a clinical, economic and social problem [1]. Even though several treatments for painful conditions have become available, pain management is still a challenging task. For instance, cancer patients can experience pain as a result of both the illness itself and its treatment methods [2,3], resulting in a tremendous burden for patients, their families, and the healthcare system. Factors that may hinder pain management include the subjectivity of the experience, lack of communication between patients and healthcare professionals, and inadequate assessment of pain. In turn, reliable pain assessment can be difficult, especially for patients who may be not able to communicate verbally or even express the sensation of pain [4,5].

Effective management of pain can improve patients' life quality [6], so several efforts have been carried out in order to make the assessment of both pain and the effectiveness of pain relief measures a priority. For instance, the Joint Commission on Accreditation of Healthcare Organizations (JCAHO) regulations now regard pain as "the fifth vital sign" and request healthcare providers to regularly perform pain assessment [7]. Furthermore, the International Association for the Study of Pain (IASP) claims that education on pain management should be added to the curricula of healthcare students, as well as to the continuing education of healthcare providers [8]. Novel educational programs for healthcare professionals have been developed to improve pain education in low- and middle-income countries [9]. To all this can be added the fact that modern technologies can be exploited to improve the accuracy and reliability in assessing pain.

Recent advances in sensing and processing technologies have led to the emergence of new technological paradigms, such as the Internet of Things (IoT). The IoT consists in to allow multiple devices with unique identities to exchange information in order to provide customized services for process automation and remote monitoring [10]. IoT-enabling technologies have been previously discussed in Ref. [11], and they include Wireless Sensor Networks (WSN), Radio Frequency Identification (RFID), ubiquitous computation and machine learning methods. Although comprehensive reviews on the application of the IoT in healthcare have been recently published [12,13], no recent studies seem to be available to examine the role that IoT has played in pain assessment and management. In an attempt to fill this gap, the present survey

E-mail address: erick.arguello00@usc.edu.co.

https://doi.org/10.1016/j.imu.2020.100298
Received 18 November 2019; Received in revised form 26 January 2020; Accepted 27 January 2020
Available online 31 January 2020

aims to (i) review the state-of-art of IoT in pain assessment and management, (ii) point out the potential benefits and challenges to further development, and (iii) provide some advice that could be useful in addressing those issues.

2. Materials and methods

2.1. Search strategy

The literature search was performed in five databases in order to cover both technological and clinical aspects of the adoption of IoT for pain assessment and management: IEEE Xplore Digital Library, Pubmed, ScienceDirect, SpringerLink, and Google Scholar. The search was conducted during February 2019 and it was limited to English language publications. All the databases were searched using a Boolean combination of the terms "Internet of Things" OR "IoT" AND "Pain assessment" OR "Pain management". The search was limited to the period comprised between the years 2000 and 2018.

2.2. Identification and selection of relevant studies

The inclusion criteria were: 1) any scientific peer-reviewed publication describing an IoT-based solution for pain assessment and/or management, 2) the solution is used or proposed for hospital environment, and 3) the term Internet of Things is explicitly used in the study. Literature reviews, as well as those studies that only presented as an abstract, were excluded. If it was not possible to download the full text of the article through university subscriptions, then that article was also excluded.

After removing duplicates and then analyzing each article, only three studies [14–16] met the inclusion criteria, so a second literature search was conducted including the terms "embedded system", "wireless mobile device", "web-based" and "cloud computing", which also appear in the IoT literature. Two new rules were added to the inclusion criteria: 4) the study describes the adoption of one or more IoT-enabling technologies (see Ref. [11] for details) for pain assessment and/or management, and 5) the solution is used either for remote or self-monitoring. Duplicates were removed and after reviewing the full text of the article, information regarding authors, study date, country, type of technology used, and if the solution was adopted for pain assessment only, for pain management only or for both pain assessment and management, was extracted from each study.

3. Results and discussion

3.1. Selection of articles

A total of 118 references were identified from the five databases. After removal of duplicates, 59 publications remained. Then, 43 publications were excluded because they did not meet the inclusion criteria. Only 16 publications satisfied the aforementioned eligibility criteria and were included for analysis.

3.2. Classification of findings

As can be seen from Table 1, the majority of the publications (11/16) were peer-reviewed journal articles and all the studies describe the use of one or more IoT-enabling technologies for pain assessment. However, only a few studies (4/16) illustrate the implementation of IoT-enabling technologies for pain management, including two publications [17,18] describing a solution specifically designed for self-management of cancer pain. Clinical trials and randomized designs were also found, although only in a minor proportion (5/16). Finally, while most of the studies were from North America and Europe, only two studies [14,19] were from Asia and no studies from Latin America were found.

3.3. The involvement of IoT-enabling technologies in pain assessment and/or management

The IoT consists of embedded technologies of sensing, transmitting and processing which could be used simultaneously for automatic, remote and real-time monitoring. Examples of the adoption of IoT-enabling technologies for pain assessment and/or management include the use of electronic diaries [20–23], which have shown significantly greater compliance and accuracy in diary recording compared to traditional paper diaries in adult and children populations with pain. With the advent of wireless mobile devices like smartphones, it is now possible to capture patients' pain data in real-time and easily

Table 1
A summary of the findings from the literature search on the role of the Internet of Things (IoT) in pain assessment and management (see text for details). HTML: HyperText Markup Language; IP: Internet Protocol; RF: Radio Frequency; SVM: Support Vector Machine; TCP: Transmission Control Protocol; UDP: User Datagram Protocol; Wi-Fi: Wireless Networking Technology IEEE 802.11x; WSN: Wireless Sensor Networks.

Ref.	Year	Country	Publication type		Type of technology	Solution's purpose	
			Journal	Proceedings		Pain Assessment	Pain Management
[14]	2018	China, Finland, Sweden	✓		WSN, Wi-Fi, UDP/TCP protocol, HTML5, k-Nearest Neighbour classifier	✓	
[15]	2011	Sweden		✓	WSN/RF, SVM classifier, Wi-Fi (852.11b and 852.11c), smart mobile devices	✓	
[16]	2018	Albania, Australia	✓		Web-based portal, smart mobile devices, Artificial Intelligence algorithms	✓	
[17]	2013	Canada	✓		Wi-Fi, web-based app, smart mobile devices	✓	
[18]	2014	Canada	✓		Soft-Computing tools, smart mobile devices, web-based app.	✓	✓
[19]	2013	India		✓	WSN, Soft-Computing tools, smart mobile devices.	✓	✓
[20]	2001	USA	✓		Smart mobile device, local server, TCP/IP protocol	✓	
[21]	2003	USA	✓		Smart mobile device, local server, TCP/IP protocol	✓	
[22]	2004	USA	✓		Smart mobile device, local server, TCP/IP protocol	✓	
[23]	2008	Sweden	✓		Digital pen, local server, TCP/IP protocol	✓	
[24]	2014	Spain	✓		Smart mobile device, local server, web-based app	✓	
[25]	2013	USA	✓		Smart mobile device, local server, web-based app	✓	✓
[28]	2017	Canada	✓		Soft-Computing tools, smart mobile devices, web-based app.	✓	✓
[29]	2014	Spain		✓	Computer vision algorithms, WSN, knowledge-based system, web-based app, smart mobile devices	✓	
[32]	2015	Germany		✓	WSN, Data-fusion, SVM classifier	✓	
[33]	2011	USA, Australia	✓		WSN, Computer vision algorithms, SVM classifier	✓	

Source: Author own creation.

upload the information for analysis by healthcare providers [16,24,25]. Interestingly, smartwatches seem to have not received as much attention as smartphones and tablets regarding their use for pain assessment and/or management [26]. This is possibly due to only a relatively small percentage of people use smartwatches for continuous physiological monitoring, as recently reported by Seifert and colleagues [27]. Some efforts have aimed to exploit the compliance-based reward system previously adopted by the electronic games industry in order to create novel and interactive pain assessment and management tools. For instance, Stintson et al. [17] developed an iPhone-based pain diary app, so-called Pain Squad, that encourages adolescents with cancer to track their pain and treatments that help to reduce it through the gamification of pain assessment recordings. By using iterative usability testing cycles involving adolescent observation and interview, the Pain Squad app was recently refined for ease of use and understanding, efficiency, and acceptability [28].

The utilization of knowledge-based systems (KBS) has been recently introduced as a powerful tool for pain assessment and management [19,29]. They would not only allow quantitative pain monitoring, but they also might assist healthcare professionals in the decision-making process. The knowledge base that KBS have can in turn be continuously updated as a result of new information received from external sources like sensing devices. Furthermore, inferences or decisions made after interpreting the meaning of that information would help to create a knowledge base that might attract the interest of the healthcare research community, which is constantly aiming to improve the way in which pain assessment and management are carried out. With the advances in wireless technology and low-power electronics, it is now possible to capture information from multiple sources and transmit it via wireless protocols, such as Bluetooth or Wi-Fi, to a local gateway. Hence the importance of filling the gap between Semantic Web technologies and data formats used in IoT devices, as outlined by several authors [30,31].

More recent approaches for achieving automatic pain assessment and management are focused on using either multiple physiological parameters [29,32] or facial expressions [15,33] as pain indicators. All these schemes demand heavy data processing, which in turn involves noise removal and parameter extraction in both time and frequency domain. In this sense, cloud computing has been proposed as a proper candidate to provide long term storage of patient's pain-related data, as well as to assist health professionals with diagnostic information. In broader terms, cloud computing can be described as the use of remote Internet-connected servers to store, manage and process data [34]. The cloud platform not only can receive and analyze the data from multiple sensors but also provides the user with easy to understand web-based visualization. However, only a few efforts have been made to integrate cloud computing with automatic pain assessment and/or management [14].

As shown in Table 1, smart mobile devices such as personal digital assistants (PDA) [20–23] and smartphones [16–19,24,25,28] are the most used tool for pain assessment and, in some cases, self-management. Specifically, smartphone applications, commonly referred to as apps, have increasingly gained popularity among different age groups around the world. Yet, the majority of pain apps are often designed by engineers rather than healthcare professionals, so they rarely adhere to clinical evidence-based practices, thereby misleading users [35]. Besides, only a few studies [18,28] have examined the apps' quality as well as their usability and compliance levels. Smart mobile devices are followed by wireless sensor networks (WSN), which have the advantage of giving patients real-time, reliable and continuous monitoring [36] with no need for the patient to provide the system with pain-related data. Support Vector Machines (SVM) seem to be the most used classifier [15,32,33] to discriminate between either pain and no pain or different pain levels. Only one study has adopted the k-nearest neighbour classifier [14]. Interestingly, no study has used Artificial Neural Networks (ANN) as classifier.

3.4. The adoption of the IoT paradigm in a pain assessment/management scenario: potential benefits, current barriers and future directions

Although no consensus has been reached in defining a universal architecture for IoT-based solutions, a typical IoT-based system consists of three layers: the perception layer, the network layer, and the application layer [10]. On the other hand, an IoT-based system for pain assessment and management might be viewed as composed of three basic elements: the measuring or input devices, the connectivity method, and the Web applications and APIs (see Fig. 1).

The measuring or input devices are responsible for capturing pain-related data, either in the form of a score or through physiological and/or behavioral monitoring. Such data are then transmitted via wireless protocols such as Wi-Fi or Bluetooth to a general router or a smart gateway, which provides continuous connectivity between the sensors and a remote or local server, so-called "the cloud", to where the pain-related data are transferred for heavy processing. Finally, the Web applications and APIs bridges the gap between healthcare staff and the system, not only by enabling physicians and nurses for real-time/offline data visualization but also by sending feedback to devices used in patient care for automatic update.

Among the potential benefits of using IoT-based systems for the assessment and management of pain are:

- The automation of pain-related data collection by means of low-cost sensing devices, which makes IoT-based system a suitable alternative for pain assessment in those groups of patients with limited cognitive and communication abilities. Moreover, healthcare providers may focus on patient care instead of spending time in constantly asking the patient how much he/she hurts.
- The customization of pain management approaches by using machine learning techniques to comprehensively analyze the pain-related data acquired and stored during the patient's hospital stay. Thus, a personalized decision-making process could be conducted, thereby minimizing diagnostic errors and increasing treatment efficacy.
- The opportunity to include relatives in patient care by providing them with real-time data remotely, which becomes particularly important if they are not able to stay in the hospital.

As outlined in the previous section, several technologies enabling the realization of the IoT have been successfully adopted in the development of systems capable of contributing to the assessment and management of pain. However, those technologies have been mostly used in isolation and only a few research groups [14,15] have been able to integrate them under the IoT philosophy. In addition, the majority of solutions are still in the testing phase and further studies are needed to evaluate their efficiency and effectiveness as a tool for pain assessment and management. IoT-based systems for pain assessment and management also must provide security and confidentiality of patients' medical information, and potential privacy issues need to be addressed at each of the layers composing the IoT architecture, as pointed out by several authors [37,38]. At the perception layer, for instance, it is necessary to ensure that only authorized people can have access to pain-related data produced by measuring or input devices. This can be achieved by defining a physical identity for each sensor and implementing an access management policy. Additionally, security techniques should adapt to the data format: multimedia compression, stenography, and encryption can be used for data collected by multivariate sensing devices, whereas image compression and cyclic redundancy check (CRC) can be applied to images acquired from patients [39].

One of the most common security issues resulting from IoT devices is denial of service (DoS) [37]. A DoS is a security attack aimed at devices that are available on the Internet or a private network. Networks switches are the first line of defense against those attacks. To achieve this, a network switch should be set to detect different types of port scans

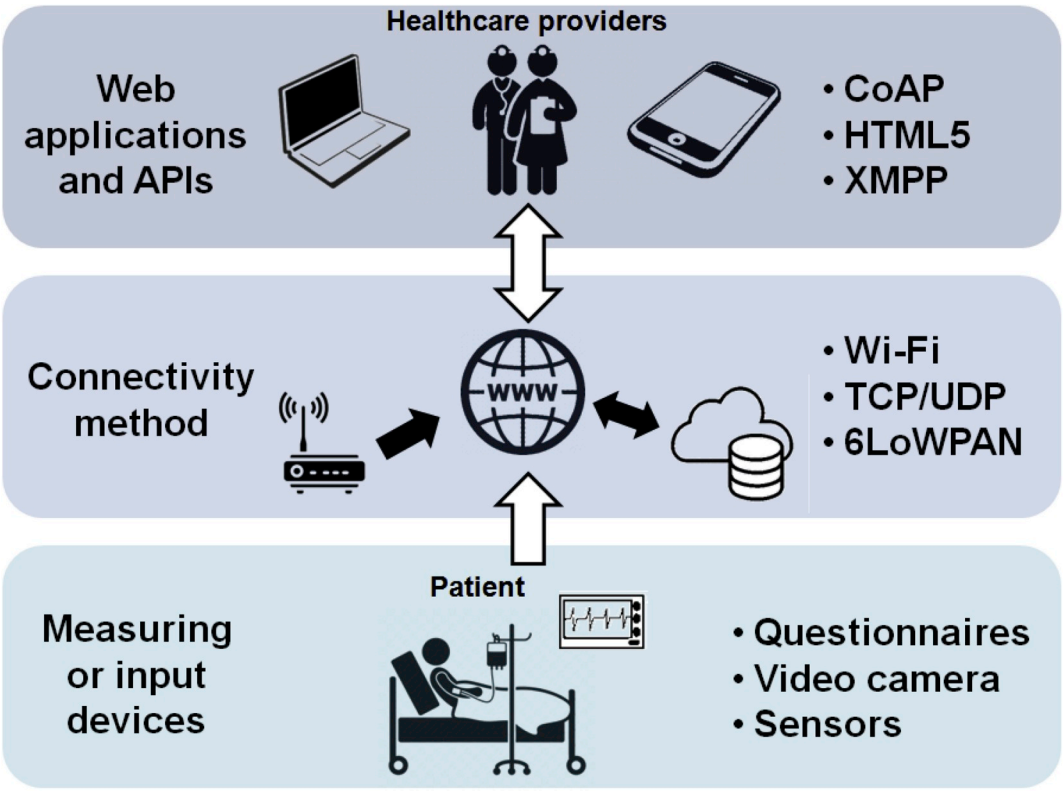

Fig. 1. A general depiction of an IoT-based system for pain assessment.
Source: Author own creation.

by monitoring for TCP or UDP packets sent to open or closed ports [38]. Regarding the data storage and processing in the cloud, system security and privacy are mandatory. Appropriate privacy-preserving measures need to be taken to prevent unauthorized parties from accessing sensitive information. Secure cloud storage frameworks have been proposed for use with personal health records [40,41]. On the other hand, secure medical data processing on the cloud remains a great concern.

Besides security and privacy issues, barriers impeding the adoption of the IoT paradigm for pain assessment and management may include the little knowledge that healthcare providers have about how IoT technologies work, as well as the fact that benefits and risks associated with the use of these tools have not yet been fully understood [42]. Nevertheless, two major challenges need to be addressed. The first one has to do with the difficulties involved in pain assessment itself. Most of the pain assessment tools used in clinical practice, as well as the majority of the IoT-based solutions listed in Table 1 (10/16), have mainly focused on the patient's self-evaluated pain. This is mainly due to intensity is a relatively easy dimension of pain experience for patients to report [43]. Still, all these methods rely on the patient's ability to inform the severity or magnitude of perceived pain, which could not be possible (or reliable) under certain circumstances [4,5]. When patients are not able to report pain, the observation of changes in behavioral or physiological parameters can be a helpful approach for pain assessment. Behavioral parameters of pain include facial expression, crying/moaning, body position, and motor restlessness [44], as well as the effect of pain on daily living activities such as eating, sleeping, and social interaction. As demonstrated by previous work [5,45], the observation of pain behaviors can be a valuable tool for pain measurement. On the other hand, the patient's level of consciousness and the degree of sedation can influence the scoring of the patient's pain behaviors [46,47]. Physiological parameters such as heart rate (HR), respiratory rate (RR), and blood pressure (BP), can also be affected by patient conditions and emotions, so several authors [48,49] argue that those markers can only be used as a preliminary cue for pain assessment. However, as suggested in Ref. [50], the reliability of this approach may be improved by using multiple parameters in order to provide a more accurate judgment.

The autonomic nervous system (ANS) is severely influenced by the experience of pain [51,52], so by monitoring physiological processes, most of which are modulated by autonomic activity, it could be possible to detect or even measure the perceived pain. Physiological parameters that have proven to be useful in revealing the presence of pain include heart rate, heart rate variability (HRV), respiratory rate, blood pressure, skin temperature, electrodermal activity (EDA) and electrical muscle activity [50,53]. On the other hand, unlike electrocardiography (ECG) and photoplethysmography (PPG), the techniques and instrumentation required for the acquisition of some of these parameters (e.g., EDA, facial surface electromyography) might be not so common and easy-to-deploy for clinical environments. Novel sensing and measuring devices require regulatory approval and training of medical personnel, thereby limiting the rate at which such innovations can be introduced [54]. Additionally, multiparameter approaches demand a great variety of sensors, which may be uncomfortable for the patient who is already in pain. This could explain the limited number of studies [14,19,29,32] proposing IoT-based solutions that use physiological parameters to detect or assess pain. Nevertheless, monitoring of physiological processes, as well as biopotential acquisition, may provide a simple and objective method for pain assessment, since it does not depend on the patient's ability to communicate and/or rate the pain he/she is experiencing. Furthermore, wearable sensing devices can easily incorporate multiple physiological measurements and enable data capture with much finer temporal resolution over much longer time scales in comparison with the examination room-based measurements commonly conducted in current clinical practice [54].

The second major challenge for adopting IoT-based systems in pain assessment and management is the lack of a pain assessment and management culture. Even though pain has been recognized as the fifth vital

sign [7] many healthcare facilities around the world still do not have a protocol or guidelines for effective assessment and management of pain. Only in the United States, more than half of patients with pain have reported inadequate treatment of their condition [55], and this percentage is even higher in low- and middle-income countries [9]. Additionally, there are several obstacles that healthcare professionals must overcome [56], to which is added the fact of having to face a new technological paradigm as IoT.

Ultimately, what is considered to be useful in addressing the aforementioned issues should come from both the engineering side and the healthcare side.

From the engineering side, the evaluation of IoT-based systems for pain assessment and management should not be limited to performance and operability tests, but it should also be carried out in terms of the usability, feasibility, compliance, and satisfaction associated with their use. Thus, healthcare providers and patients can familiarize with these technologies and objectively evaluate how suitable they are for the assessment and management of pain. Several authors [17,18,22,24,28] have proved that the utilization of IoT-enabling technologies may help to improve the accuracy of pain assessment and attain high levels of compliance and usability. This small, although not negligible, amount of evidence should be made available to healthcare practitioners in order to increase their trust in this kind of technologies. As outlined in Ref. [16], future developments need to include the expertise of clinical researchers and healthcare providers, even from the very design phase.

From the healthcare side, a greater awareness on the part of physicians and nurses regarding the role that IoT-enabling technologies have played in the assessment and management of pain is an essential requirement. Likewise, it is necessary to achieve a better understanding of not only the benefits but also the risks involved in the implementation of IoT-based systems in the hospital environment. On the other hand, all this will be meaningless until healthcare providers start at once to adopt a pain assessment and management culture, and until further efforts to overcome the barriers impeding the assessment of pain as another vital sign are undertaken.

4. Conclusions

Although there are examples of the use of IoT in pain assessment and management, the field is still in its infancy. Technologies enabling the realization of the IoT have been used in isolation rather than combined under the IoT philosophy, and further implementations and research are needed to ensure feasibility and acceptance of proposed solutions. Nevertheless, there is a little, but not insignificant evidence showing that IoT-enabling technologies may help to improve the accuracy of pain assessment, as well as to attain high levels of usability and compliance. Such evidence should be made available to physicians and nurses in order to allow them to familiarize themselves with that kind of technologies and, therefore, to improve their trust in them. Further collaboration between healthcare providers and engineers is needed to develop innovative pain assessment and management tools following both the IoT architecture and evidence-based guidelines. All this must be done on the basis of a pain assessment and management culture, which really needs to be considered as a priority among healthcare practitioners, especially in low- and middle-income countries.

Author statement

The author declares that he holds the economic and moral rights of the material, as well as the entire and exclusive copyright of the material. This manuscript is an original work, it has not been published before and it is not under consideration for publication by another Journal, in English and in foreign translations, in all format and media of expression, including print or electronic. There is no conflict of interest influencing the research or the content of the manuscript. If the paper is published, the author will transfer the copyrights to the Informatics in Medicine Unlocked, and he understands that the material cannot be reproduced without the journal's permission.

Ethical statement and author agreement

The author declares that the manuscript is an original work, it has not been published before and it is not under consideration for publication by another Journal, in English and in foreign translations, in all format and media of expression, including print or electronic. If the paper is published, the author will transfer the copyrights to the Informatics in Medicine Unlocked, and understand that the material cannot be reproduced without the journal's permission.

Declaration of competing interest

The author declares that **there is no conflict of interest** influencing the research or the content of the manuscript.

Acknowledgement

The publication of this work was financed by Dirección General de Investigaciones (DGI) of Universidad Santiago de Cali through the project 819-621118-259.

The author would like to express his gratitude to Danny Aurora Valera Bermúdez for her useful comments in early and final drafts of the manuscript.

References

[1] Duke G, Haas BK, Yarbrough S, Northam S. Pain management knowledge and attitudes of baccalaureate nursing students and faculty. Pain Manag Nurs 2013;14(1):11–9.
[2] Fortier MA, Wahi A, Maurer EL, Tan ET, Sender LS, Kain ZN. Attitudes regarding analgesic use and pain expression in parents of children with cancer. J Pediatr Hematol/Oncol 2012;34(4):257–62.
[3] Breivik H, Cherny N, Collett B, de Conno F, Filbet M, Foubert AJ, Cohen R, Dow L. Cancer-related pain: a pan-European survey of prevalence, treatment, and patient attitudes. Ann Oncol 2009;20(8):1420–33.
[4] Barr J, Fraser GL, Puntillo K, Ely EW, Gélinas C, Dasta JF, Davidson JE, Devlin JW, Kress JP, Joffe AM, Coursin DB, Herr DL, Tung A, Robinson BRH, Fontaine DK, Ramsay MA, Riker RR, Sessler C. Clinical practice guidelines for the management of pain, agitation, and delirium in adult patients in the in-tensive care unit. Crit Care Med 2013;41(1):263–306.
[5] Herr K, Coyne PJ, McCaffery M, Manworren R, Merkel S. Pain assessment in the patient unable to self-report: position statement with clinical practice recommendations. Pain Manag Nurs 2011;12(4):230–50.
[6] Katz N. The impact of pain management on quality of life. J Pain Symptom Manag 2002;24(1):S38–47.
[7] Joint Commission on Accreditation of Healthcare Organizations. R3 Report Issue 20: pain assessment and management standards for behavioral health care. Available at: https://www.jointcommission.org/r3_report_20_pain_assesment_and_management_standards_for_bhc/?j=3975180&e=jdepaolis@jointcommission.org&l=94_HTML&u=137057407&mid=1064717&jb=5. [Accessed 9 March 2019].
[8] Kopf A, Patel NB. Guide to pain management in low-resource settings. Seattle, USA: IASP; 2010. Available at: https://crh.arizona.edu/sites/default/files/u35/Guide_to_Pain_Management_in_Low-Resource_Settings.pdf. [Accessed 17 February 2019].
[9] Goucke CR, Jackson T, Morriss W, Royle J. Essential pain management: an educational program for health care workers. World J Surg 2015;39(4):865–70.
[10] Silva BN, Khan M, Han K. Internet of things: a comprehensive review of enabling technologies, architecture, and challenges. IETE Tech Rev 2018;35(2):205–20.
[11] Gubbi J, Buyyab G, Marusica S, Palaniswami M. Internet of things (IoT): a vision, architectural elements. Future Generat Comput Syst 2013;29(7):1645–60.
[12] Baker SB, Xiang W, Atkinson I. Internet of things for smart healthcare: technologies, challenges, and opportunities. IEEE Access 2017;5:26521–44.
[13] Yuehong YIN, Zeng Y, Chen X, Fan Y. The internet of things in healthcare: an overview. J Ind Inf Integr 2016;1:3–13.
[14] Yang G, Jiang M, Ouyang W, Ji G, Xie H, Rahmani AM, Liljeberg P, Tenhunen H. IoT-based remote pain monitoring system: from device to cloud platform. IEEE J Biomed Health Inf 2018;22(6):1711–9.
[15] Zhong Y, Liu L. Remote neonatal pain assessment system based on internet of things. In: Proc 2011 int conf IoT 4th int conf cyber phys soc comput; 2011. p. 629–33.
[16] Atee M, Hoti K, Hughes JD. A technical note on the PainChek™ system: a web portal and mobile medical device for assessing pain in people with dementia. Front Aging Neurosci 2018;10(117):1–13.

[17] Stinson JN, Jibb LA, Nguyen C, Nathan PC, Maloney AM, Dupuis LL, Gerstle JT, Alman B, Hopyan S, Strahlendorf C, Portwine C, Johnston DL, Orr M. Development and testing of a multidimensional iPhone pain assessment application for adolescents with cancer. J Med Internet Res 2013;15(3):e51.
[18] Jibb LA, Stevens BJ, Nathan PC, Seto E, Cafazzo JA, Stinson JN. A smartphone-based pain management app for adolescents with cancer: establishing system requirements and a pain care algorithm based on literature review, interviews, and consensus. JMIR Res Protoc 2014;3(1):e15.
[19] Rajesh M, Muthu JS, Suseela G. iPainRelief-A pain assessment and management app for a smart phone implementing sensors and soft computing tools. In: Proc 2013 int conf inf commun emb syst (ICICES); 2013. p. 434–41.
[20] Jamison RN, Raymond SA, Levine JG, Slawsby EA, Nedeljkovic SS, Katz NP. Electronic diaries for monitoring chronic pain: 1-year validation study. Pain 2001;91(3):277–85.
[21] Stone AA, Broderick JE, Schwartz JE, Shiffman S, Litcher-Kelly L, Calvanese P. Intensive momentary reporting of pain with an electronic diary: reactivity, compliance, and patient satisfaction. Pain 2003;104(1–2):343–51.
[22] Palermo TM, Valenzuela D, Stork PP. A randomized trial of electronic versus paper pain diaries in children: impact of compliance, accuracy, and acceptability. Pain 2004;107(3):213–9.
[23] Lind L, Karlsson D, Fridlund B. Patients' use of digital pens for pain assessment in advanced palliative home healthcare. Int J Med Inf 2008;72(2):129–36.
[24] De la Vega R, Roset R, Castarlenas E, Sánchez-Rodríguez E, Solé E, Miró J. Development and testing of painometer: a smartphone app to assess pain intensity. J Pain 2014;15(10):1001–7.
[25] Jacob E, Duran J, Stinson J, Lewis MA, Zeltzer L. Remote monitoring of pain and symptoms using wireless technology in children and adolescents with sickle cell disease. J Am Acad Nurse Pract 2013;25(1):42–54.
[26] Manini TM, Mendoza T, Battula M, Davoudi A, Kheirkhahan M, Young ME, Weber E, Fillingim RB, Rashidi P. Perception of older adults toward smartwatch technology for assessing pain and related patient-reported outcomes: pilot study. JMIR mHealth uHealth 2019;7(3):e10044.
[27] Seifert A, Schlomann A, Rietz C, Schelling HR. The use of mobile devices for physical activity tracking in older adults' everyday life. Dig Health 2017;3. 2055207617740088.
[28] Jibb LA, Cafazzo JA, Nathan PC, Seto E, Stevens BJ, Nguyen C, Stinson JN. Development of a mHealth real-time pain self-management app for adolescents with cancer: an iterative usability testing study. J Pediatr Oncol Nurs 2017;34(4):283–94.
[29] Martínez-Ballesté A, Casanovas-Marsal JO, Solanas A, Casino F, García-Martínez M. An autonomous system to assess, display and communicate the pain level in newborns. In: Proc 2014 IEEE int symp med meas app (MeMeA); 2014. p. 1–5.
[30] Su X, Zhang H, Riekki J, Keränen A, Nurminen JK, Du L. Connecting IoT sensors to knowledge-based systems by transforming SenML to RDF. Procedia Comput Sci 2014;32:215–22.
[31] Perera C, Vasilakos AV. A knowledge-based resource discovery for Internet of Things. Knowl Base Syst 2016;109:122–36.
[32] Kächele M, Werner P, Al-Hamadi A, Palm G, Walter S, Schwenker F. Bio-visual fusion for person-independent recognition of pain intensity. In: Proc int work mult class syst; 2015. p. 220–30.
[33] Lucey P, Cohn JF, Matthews I, Lucey S, Sridharan S, Howlett J, Prkachin KM. Automatically detecting pain in video through facial action units. IEEE Trans Syst Man Cybern B Cybern 2011;41(3):664–74.
[34] Buyya R, Yeo CS, Venugopal S, Broberg J, Brandic I. Cloud computing and emerging IT platforms: vision, hype, and reality for delivering computing as the 5th utility. Future Generat Comput Syst 2009;25(6):599–616.
[35] Portelli P, Eldred C. A quality review of smartphone applications for the management of pain. Br J Pain 2016;10(3):135–40.
[36] Pantelopoulos A, Bourbakis NG. A survey on wearable sensor-based systems for health monitoring and prognosis. IEEE Trans Syst Man Cybern C Appl Rev 2010;40(1):1–12.
[37] Leloglu E. A review of security concerns in Internet of Things. J Comput Commun 2017;5(1):121–36.
[38] Yang X, Li Z, Geng Z, Zhang H. A multi-layer security model for internet of things. In: Wang Y, Zhang X, editors. Internet of Things. Berlin, Heildenberg: Springer; 2012. p. 388–93.
[39] Sujitha R, Raghavan NV, Suganya KS, Devipriya A. A novel survey on internet of things, security and its application. Int J Adv Inf Commun Technol 2014;1(8):726–9.
[40] Li M, Yu S, Zheng Y, Ren K, Lou W. Scalable and secure sharing of personal health records in cloud computing using attribute-based encryption. IEEE Trans Parallel Distr Syst 2012;24(1):131–43.
[41] Ruj S, Stojmenovic M, Nayak A. Privacy preserving access control with authentication for securing data in clouds. In: 12th IEEE/ACM international symposium on cluster, cloud and grid computing (ccgrid 2012); 2012. p. 556–63.
[42] Mieronkoski R, Azimi I, Rahmani AM, Aantaa R, Terävä V, Liljeberg P, Salanterä S. The Internet of Things for basic nursing care—a scoping review. Int J Nurs Stud 2017;69:78–90.
[43] Von Korff M, Jensen MP, Karoly P. Assessing global pain severity by self-report in clinical and health services research. Spine 2000;25(24):3140–51.
[44] Arbour C, Gelinas C. Behavioral and physiologic indicators of pain in nonverbal patients with a traumatic brain injury: an integrative review. Pain Manag Nurs 2014;15(2):506–18.
[45] Odhner M, Wegman D, Freeland N, Steinmetz A, Ingersoll GL. Assessing pain control in nonverbal critically ill adults. Dimens Crit Care Nurs 2003;22(6):260–7.
[46] Gélinas C, Johnston C. Pain assessment in the critically ill ventilated adult: validation of the Critical-Care Pain Observation Tool and physiologic indicators. Clin J Pain 2007;23(6):497–505.
[47] Payen JF, Bru O, Bosson JL, Lagrasta A, Novel E, Deschaux I, Lavagne P, Jacquot C. Assessing pain in critically ill sedated patients by using a behavioral pain scale. Crit Care Med 2001;29(12):2258–63.
[48] Chen HJ, Chen YM. Pain assessment: validation of the physiologic indicators in the ventilated adult patient. Pain Manag Nurs 2015;16(2):105–11.
[49] Cowen R, Stasiowska MK, Laycock HBC. Assessing pain objectively: the use of physiological markers. Anaesthesia 2015;70(7):828–47.
[50] Treister R, Kliger M, Zuckerman G, Aryeh IG, Eisenberg E. Differentiating between heat pain intensities: the combined effect of multiple autonomic parameters. Pain 2012;153(9):1807–14.
[51] Seifert F, Schuberth N, De Col R, Peltz E, Nickel FT, Maihöfner C. Brain activity during sympathetic response in anticipation and experience of pain. Hum Brain Mapp 2013;34(8):1768–82.
[52] Schlereth T, Birklein F. The sympathetic nervous system and pain. NeuroMolecular Med 2008;10(3):141–7.
[53] Gruss S, Treister R, Werner P, Traue HC, Crawcour S, Andrade A, Walter S. Pain intensity recognition rates via biopotential feature patterns with support vector machines. PloS One 2015;10(10).
[54] Hassanalieragh M, Page A, Soyata T, Sharma G, Aktas M, Mateos G, Kantarci B, Andreescu S. Health monitoring and management using Internet-of-Things (IoT) sensing with cloud-based processing: opportunities and challenges. In: 2015 IEEE international conference on services computing; 2015. p. 285–92.
[55] Pizzo PA, Clark NM. Alleviating suffering 101—pain relief in the United States. N Engl J Med 2012;366(3):197–9.
[56] Valério AF, Fernandes KDS, Miranda G, Terra FDS. Difficulties faced by nurses to use pain as the fifth vital sign and the mechanisms/actions adopted: an integrative review. BrJP 2019;2(1):67–71.