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Review

The landscape of research on smartphone medical apps: Coherent taxonomy, motivations, open challenges and recommendations

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ABSTRACT

Objective: To survey researchers' efforts in response to the new and disruptive technology of smartphone medical apps, mapping the research landscape form the literature into a coherent taxonomy, and finding out basic characteristics of this emerging field represented on: motivation of using smartphone apps in medicine and healthcare, open challenges that hinder the utility, and the recommendations to improve the acceptance and use of medical apps in the literature.

Methods: We performed a focused search for every article on (1) smartphone (2) medical or health-related (3) app, in four major databases: MEDLINE, Web of Science, ScienceDirect, and IEEE Xplore. Those databases are deemed broad enough to cover both medical and technical literature.

Results: The final set included 133 articles. Most articles (68/133) are reviews and surveys that refer to actual apps or the literature to describe medical apps for a specific specialty, disease, or purpose; or to provide a general overview of the technology. Another group (43/133) carried various studies, from evaluation of apps to exploration of desired features when developing them. Few researchers (17/133) presented actual attempts to develop medical apps, or shared their experiences in doing so. The smallest portion (5/133) proposed general frameworks addressing the production or operation of apps.

Discussion: Since 2010, researchers followed the trend of medical apps in several ways, though leaving areas or aspect for further attention. Regardless of their category, articles focus on the challenges that hinder the full utility of medical apps and do recommend mitigations to them.

Conclusions: Research on smartphone medical apps is active and various. We hope that this survey contribute to the understanding of the available options and gaps for other researchers to join this line of research.

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1. Introduction

Adoption of smartphones in the arsenal of healthcare is coming as no surprise. People have always used available facilities to enhance their most important activities and protect their most valuable assets; and no asset is more valuable than their own health. The utilization of information and communication technology in the practice of healthcare introduced the notion of eHealth [1,2], where telecommunications is enabling telemedicine, computers are processing health data, and the Internet is providing the infrastructure to exchange all sorts of medical information and services. When mobility became possible, telecommunications occurred through mobile phones, and computers moved along with people in the form of portable laptops and then handheld devices. The eHealth stretched to include mobile health (mHealth) [3]; but still, the phone was a phone and the computer was a computer; until both converged into a single unit known as a "smartphone".

Smartphones are mobile devices that are *smarter* than earlier generations of cellular phones, usually known as feature-phones [4]. This extra smartness is gained by virtue of closer resemblance to personal computers (PCs). Smartphones possess greater computing power, more connectivity options, sophisticated operating systems, full Internet access, and most importantly the ability to install and run third-party applications, often dubbed as "apps". This last feature extended the smartphone's versatility into new functions unthought-of before, even by its designers. However, smartphones are not just scaled down versions of their PC relatives; they depart from traditional PCs in several ways. They are portable, even beyond the portability of laptops, and they are meant to be mobile and used on the move. This introduces the notion of context to smartphones, in terms of location, ambient, and user actions. Smartphones can measure these variables via onboard sensors, such as accelerometers and gyroscopes, which are unique to smartphone platforms. Smartphones also enjoy the ultimate connectivity among computing devices, with multiple wireless interfaces to cellular networks, WiFi access points, Bluetooth peripherals, up to the latest innovations of WiFi Direct and the Near Field Communication (NFC) technologies.

Being this disruptive, smartphones are also the most personal computers so far. They are carried everywhere, and used to run all sort of functions, most of which are intimate to the users. In the context of healthcare, the trend of seeking health information from the internet is an obvious option on mobile platforms, but the real change came through the surge of apps written by developers to serve a wide variety of medical and healthcare scenarios, such as health education, intervention and adherence enhancement, as well as medication and diagnosis. Apps targeted both health professionals, patients, and the public, in the form of medical references, calculators, through the way to being attachments or alternatives to medical devices [3,5–7]. In essence, what physicians and patients had to access on stationary computers have been brought to them by apps right onto their hands/pockets, augmented by innovative use of the new sensing capabilities that required previously special equipment, external to the computing device.

The unique characteristic of mHealth, and particularly that based on smartphone apps is that it has grown very fast, outpacing the governmental efforts in regulation, as well as the health informatics researchers in study and evaluation. It is not feasible to review, let alone evaluate, the 100,000 medical-related apps available online for the major smartphone platforms [8], but those apps are actually open in the wild for download and use by healthcare professionals as well as the public. In fact, legislation of these apps itself is still debateable [9]. Apps are stored centrally in web-based repositories called app stores, a one-stop-shop fashion for marketing apps. The most popular smartphones today, with a market share of 84.4% and 11.7%, respectively [10] are the Android [11] and iOS [12] supported-phones; their corresponding online markets are Google Play [13] and Apple Apps Store [14], respectively.

Our main objective in this paper is to shed some light on researchers' efforts in response to the new and disruptive technology, mapping the research landscape form the literature into a coherent taxonomy, finding out along the way few features that characterize this emerging line of research.

2. Method

The most important keyword in the scope of this paper is "apps". This excludes any non-smartphone applications such as those found on PDAs as well as any non-apps use of smartphones such as SMS interventions. We also limit our scope to the English literature, but consider all health-related areas, including the general category of fitness and weight loss.

2.1. *Information sources*

We chose four digital databases to conduct the search for target articles: (1) the MEDLINE database covering life sciences and biomedical journals through the PubMed search engine; (2) the ScienceDirect database offering access to science, technical and medical (STM) journal articles; (3) the IEEE Xplore library of technical literature in engineering and technology; and (4) the Web of Science (WoS) service, indexing cross-disciplinary research in sciences, social sciences, arts and humanities. The rationale behind this selection is to cover both medical and technical literature, and provide a broader view of researchers' efforts in a wide, but relevant, range of disciplines.

2.2. *Study selection*

The process of study selection consisted of searching the literature sources, followed by two iterations of screening and filtering. The first iteration excluded the duplicates and irrelevant articles by scanning the titles and abstracts, while the second iteration filtered the articles after a thorough full-text reading of the screened articles from the first step. Both iterations applied the same eligibility criteria followed by four authors who performed the screening, and reviewed by two other authors.

2.3. *Search*

The search was conducted at the start of September 2014, in PubMed, ScienceDirect, IEEE Xplore and WoS databases via their search boxes. We used a mix of keywords that contained "medical", "healthcare", "smartphone" and "apps" in different variations, combined by the "OR" operator. The exact query text is shown at the top of Fig. 1. We further used the options in each search engine to exclude book chapters and other types of reports other than journal and conference articles, as we deemed those two venues the most probable to include up-to-date and proper scientific works relevant to our survey on this emergent trend of mHealth.

2.4. *Eligibility criteria*

Every article that met the criteria listed in Fig. 1 was included. We have set an initial target of mapping the space of research on medical apps into a general and coarse-grained taxonomy of four categories. These categories were derived from a pre-survey of the literature with no constraint (Google Scholar was used to obtain a first taste on the landscape and directions in the literature). After the initial removal of duplicates, articles were excluded in both iterations of screening and filtering if they did not fulfil the eligibility criteria. Examples of exclusion reasons include: (1) the article is non-English; (2) the focus is on a specific aspect of smartphone use like social networking; and (3) the target is the general mHealth technology rather than smartphone apps specifically.

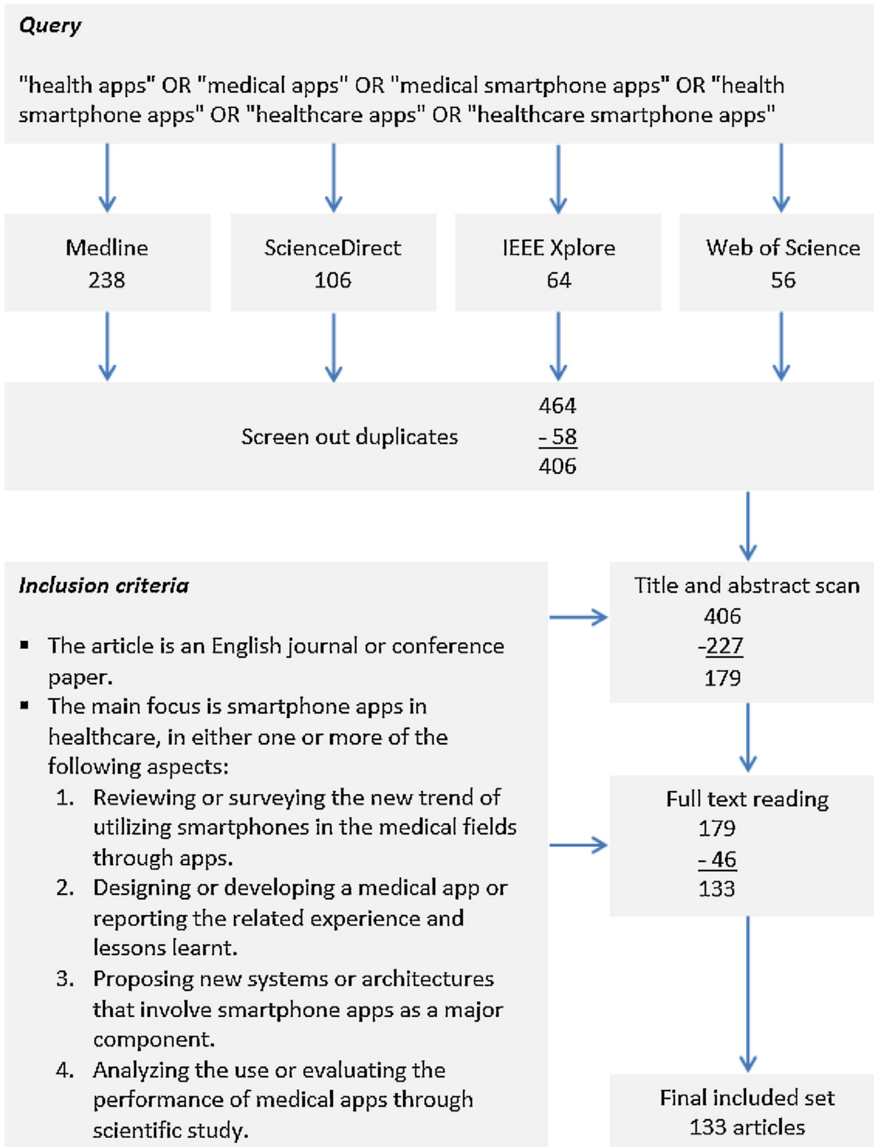

Fig. 1 – Flowchart of study selection, including the search query and inclusion criteria.

2.5. *Data collection process*

In order to simplify further steps, a full list of all included papers, with their corresponding initial categories was compiled from the various sources into a single EXCEL® file. Several full-text readings were performed by four authors, and resulted in a large collection of highlights and comments on the surveyed works, as well as in a running classification of the articles into a refined taxonomy. All comments were saved on the body of the texts (depending on each author's preferred style, either on hard or soft copy versions). This was followed by the process of summarization, tabulation and description of the main findings. Sets of relevant information were saved in WORD® and EXCEL® files, including the full list of articles, their respective source databases, summary and description tables, categorization tables based on medical specialties, purposes, review sources, target platforms and audiences, as well as various related figures. Those datasets are provided in the supplemental materials as a complete reference for the results described next.

3. Results

The initial query search resulted in 464 articles: 238 from MEDLINE database, 106 from ScienceDirect, 64 from IEEE Xplore, and 56 articles from WoS, over the span form 2010 to 2014. Fifty-eight (58) articles were duplicates among the four library databases. After scanning the titles and abstracts, 227 more articles were excluded, resulting in 179 papers. Full-text reading excluded 46 articles, leaving 133 articles in the final included set. Those papers were read thoroughly in the main purpose of finding out a general map for the conducted research on this emerging topic. Most of the articles (51.13%; 68/133) are review and survey papers that refer to actual apps or the literature in order to describe the existing medical apps

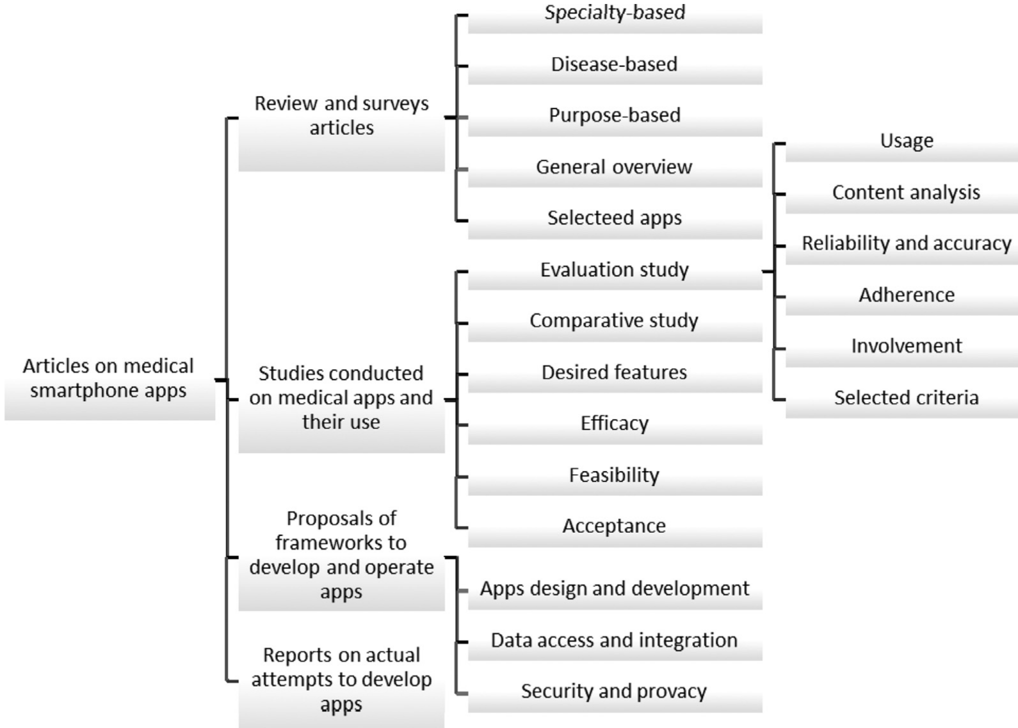

Fig. 2 – A taxonomy of research literature on smartphone medical apps.

for a specific specialty, disease, or purpose, or to provide a general overview of the new trend. The next largest portion of articles (32.33%; 43/133) conducted various studies, ranging from seeking to evaluate samples from the flowing current of medical apps to exploring the desired features that people would like to have in their newly found helper tools. Quite a few researchers (12.78%; 17/133) moved along the new wave and presented actual attempts to develop their own medical apps, or shared their experiences in doing so. The final and smallest portion of works (3.76%; 5/133) included proposals for frameworks or models that address the operation of apps or their development in the more general setting. We have observed these patterns, captured the general categories of research articles, and then refined the classification into the literature taxonomy shown in Fig. 2. We could distinguish between several subcategories in the main classes, though overlaps do happen. In the following sections, we list the observed categories, making simple statistics throughout the discussion.

3.1. *Review and survey articles*

It comes as no surprise that the earliest and most research works on medical apps are review articles that aimed to capture the new phenomena, introduce it to the medical community, and derive some descriptive statistics, trying to understand the implications and potentials along the way. The easiest and largest class to notice is the reviews based on a specific specialty or disease [15–61] (47/68 articles). Examples of this category include the reviews of apps on Anaesthesia [15,20,48,62,63], Surgery [16,21,37,38,59,60,64], Plastic surgery [24,42,54,62], Oncology [17,28,49,53,65,66], Palliative medicine [41,57,67,68], Ophthalmology [26,56], Dentistry [18,39,40], Pharmacy [30,69–71], Psychiatry [34,55,72–75], Paediatrics [31,58,76–82], Infectious Diseases [25,27,29,35,44,83–86], Public health [28,33,36,51,87–105], Women health [22,52,61], Dermatology [32,106,107], Family medicine [23,77], Endocrinology [43], Cardiopulmonary Resuscitation [50], Rehabilitation [45,108], Asthma [97,109], Internal medicine [19,77,110,111], Cardiology [46,97,112], and Sports medicine [47]. A smaller group of articles provides general overviews of medical apps and their benefits or impacts [3,6,7,113–119] (10/68). Despite their generality, few of these surveys emphasize special aspects, such as the integration of social networking with medical apps [115], the perspective of developers [7], the sensing capabilities of smartphones [114], or the legal challenges and federal regulations of apps [117]. Another few papers (11/68) review apps in the context of specific purposes rather than specific specialties or general views, including apps as references [70,120,121], apps for pain management [67,68], clinical management [89], pre-operative settings [122], medical adherence [71], wellness [5], tobacco cessation [103], and even apps for pro-smoking [102] (to raise awareness of harmful apps).

3.1.1. *Sources of the reviews*

Review articles might consult the online app stores directly (38/68), or refer to the literature (15/68). They might also refer to both sources (9/68). Two articles based their review on interviews with healthcare professionals [16,119], while Campbell et al. [114] reviewed apps developed by their team. Most of the reviews on specific specialties or purposes rely on actual apps from the online stores, while most of the general surveys

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Table 1 – Primary sources of review articles by review subcategories.

	Online markets	Literature	Both	Interviews	Own projects	n/a	Total
Specialty-based	29	6	8	1	0	3	47
Purpose-based	8	2	1	0	0	0	11
General overview	1	7	0	1	1	0	10
Total	38	15	9	2	1	3	**68**

Significance of the bold value: To figure out the number of manuscript per topic on Smartphone Medical Apps; Research focus on Smartphone Medical Apps; Well-observed topics on Smartphone Medical Apps; Unobserved topic on Smartphone Medical Apps.

refer to other works instead. Table 1 breaks down the sources of reviews based on these subcategories.

3.2. *Studies conducted on medical apps and their use*

Despite the frequent complaint in literature about the lack of works that study and assess the phenomena of medical apps compared to just reporting on them, we found that around a third of our sample (43/133) is articles conducting studies in one form or another [50,62–65,69,72,73,75–88, 90,92,96,98,99,101,104–109,111,123–131]. We divided the included works into a large category of evaluation studies (29/43), and a few other smaller categories (14/43). These categories attempt to compare between medical apps or between apps and other tools (5/43), explore the desired features sought by users in medical apps (4/43), study the efficacy of medical apps (2/43), check their feasibility in certain situations (2/43), or examine clinician acceptance of using them (1/43). Among evaluation studies, the most popular criteria is the usage patterns of apps by physicians [108,125,128,130], medical students [127,131], or patients [75,124]. Other studies perform content analysis of apps on smoking cessation [90,104], asthma self-management [109], weight management [98], addiction recovery [96], or references of infectious diseases [85]. Arguably, the most sought after studies are those that test the accuracy and reliability of apps. Available studies in this direction are still few, evaluating either the precision of apps measurement compared to traditional tools [79,82,126], the accuracy their calculations [69,111], or the reliability of their assessment [107]. A related class to these studies is the articles that address the adherence of medical apps to regulations and established guidelines, especially those related to evidence-based behaviour change [78,101,105], and diabetes self-management [88]. Other evaluation studies examine the involvement of healthcare professionals in the development of medical apps [64,86,106], or evaluate apps against a specific set of selected criteria [83,84,123].

Apart from evaluations, few works compare between two medical apps [62,63], between an app and traditional website and paper-based tools [87], or between an app and smartphone-based website access [77]. Another group of studies reported lessons on the design and best practices of developing medical apps with features in demand [76,92,99,129]. A couple of studies examined efficacy of medical apps: whether the use of apps can improve performance of trainees in newborn intubation [81], and effectiveness of apps in suicide prevention [73]. Another couple of apps addressed the feasibility of using medical apps on either daily collection of self-reporting data [65], or as immunization reminder systems [80]. Finally, Kuhn et al. investigated the acceptance of mental-health clinician to a future medical app based on its description [72].

3.2.1. *Bases of the studies*

Most of the articles in the study category base their analysis on actual downloaded apps (29/43), which is necessary for studies that analyze the accuracy or any real output of the apps. In contrast, many studies refer to the description of apps on their websites or corresponding pages on the online stores (10/43); for example to find out about any declared involvement of medical references or healthcare personnel. Surveys and questionnaires are particularly used in studies of apps usage (4/43). Some studies even develop their own apps to experiment with (4/43). Yet, few studies might rely on the literature, mock-ups of apps design or on focus groups (2/43, 1/43 and 1/43, respectively).

3.3. *Reports on actual attempts to develop apps*

The literature on medical apps includes active attempts to participate in the new trend and develop apps by the researchers themselves (mostly professionals from healthcare disciplines) (17/133). The first such attempt was published in 2010, proposing the use of web apps to collect patients' data [132]. A popular choice among articles in this category is to develop physical-activity behaviour change and fitness apps [91,95,100]. Most papers from IEEE conferences (7/12) appear in this category, reporting on the development of medical apps [66,74], proposing the use of hardware capabilities like barcode and RFID tags [133], and the use of data mining [134], or proposing complete designs of apps [135]. A couple of articles demonstrate the use of motion sensors [94,136]. Other options in this category include the development of educational apps [112]. The rest of apps-development articles include reports on apps to facilitate public observations collection [93], collaboration among researchers [137], or assist international patients by translating medical terms [138]. One article targets patients of colorectal cancer via early screening service [110], and the final article in this category reports a large-scale experience with developing 12 health apps in the largest tertiary hospital in Korea [139].

When talking about development, the choice of platform is pertinent. Most of the first medical apps were developed for Apple iOS (through iPhone or iPad devices), as the commencement of this platform predated Google Android (2007 and 2008 respectively). However, most of the research development works in our sample targeted the Android or both platforms (7/17 and 4/17, respectively). Five articles developed for the iOS, and one article chose to develop a cross-platform, web-based app. As of the target audience of the developed

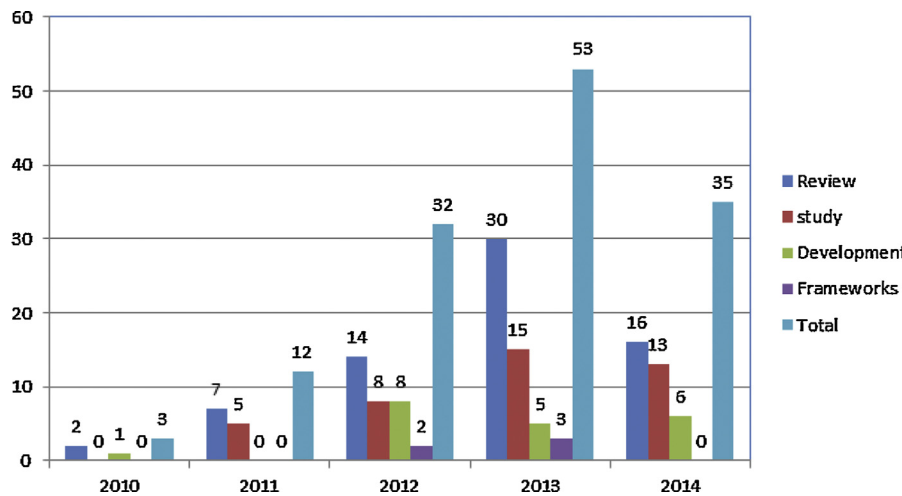

Fig. 3 – Number of included articles in different categories by year of publication.

medical apps in our sample, the majority of apps targeted the patients or the public (12/17), two apps targeted medical staff, and three apps targeted both groups.

Ten of the articles developing medical apps explicitly stated the involvement of external professionals of the subject matter in addition to the authors. Those professionals included software developers [91,132]; personal from marketing, nutrition and dietetics, physical activity and information technology [95]; two psychologists, a software engineering expert, an Objective-C developer and a media designer [74]; software developers, information scientists and end-users [93]; information technology staff [137]; computer scientists, psychologists, epidemiologists, exercise scientists, graphic designers and end users [94]; a professional web developer [112]; an information technology alliance company [139]; as well as doctors and patients [135].

3.4. *Proposals of frameworks to develop and operate apps*

The final category in our taxonomy is articles that cannot be fit in the previous group of articles, since they do not develop new apps, but rather introduce overall frameworks or models for the development or use of them. Articles in this class (5/133) include either works focusing on models and methods for the design [97, 1059] or development of medical apps [140, 1076]. Another couple of articles introduce frameworks for data access and integration between apps and other parts of health information systems [141,142]. Finally, a single work addresses the issue of secure exchange of medical apps' data, proposing a cooperative environment with data encryption framework [143]. This category of articles is currently attracting the least attention among researchers as apparent from Fig. 3, which shows the number of articles in each category of our taxonomy along the years from 2010 to September 2014. Nevertheless, we expect that devising frameworks for the production and operation of medical apps within the big picture of health informatics would receive more interest as the demand for general and scalable solutions for the current challenges increase.

3.5. *Articles by medical specialty of apps*

It is probably interesting to find out which medical fields are served by the new medical apps and to which extent. Fig. 4 shows the number of articles by the specialty of which their apps cover. The shown articles do not include the full list (133), because the specialties of the addressed apps in 30 articles are not available or not applicable (e.g. the case of proposing general frameworks for apps development). The articles neither add up to 103, since the apps in few articles fall in more than one specialty.

3.6. *Articles by purpose and function of apps*

Medical apps generally serve particular purposes or functions. Examples include the functions of information reference, education, self-management, clinical practice and diagnosis. Excluding the review articles (since each review usually surveys apps from the whole range of functions), we show the number of articles from the other categories detailed by the purpose of apps they address in Fig. 5. The value of this figure is to gain an insight into the most visited functions by studies and development efforts, and those that need more attention. The list in Fig. 5 misses nine articles, where we could not find the specific purpose of the subjected apps.

3.7. *Articles by indexing databases*

Fig. 6 depicts the distribution of articles from different categories over the digital databases in which we performed the search. The purpose is to highlight the potential venues for seeking (as well as publishing) works on medical apps. It seems that the disciplines of life and medical sciences are more interested in this subject, which is to be expected. It is also important to note that the figures in this graph are not consistent with the numbers of articles we initially found in each database. For example, the initial query against WoS index triggered only 56 results before any exclusion, while Fig. 6 shows 86 articles of the final set in WoS. The reason for this discrepancy is that the initial query failed to pull out

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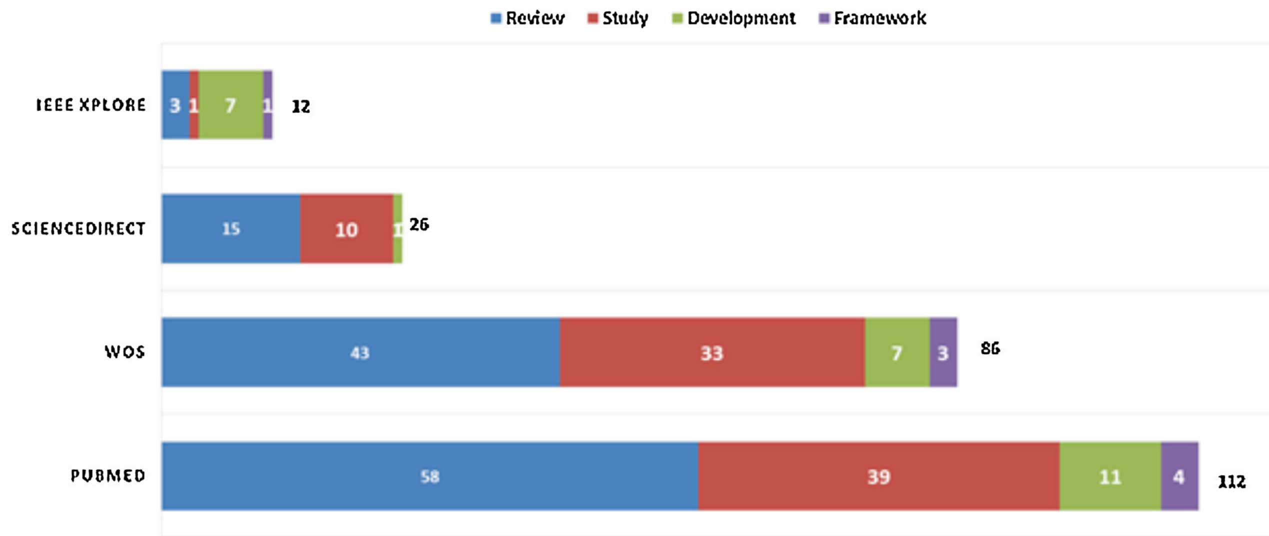

Fig. 4 – Number of included articles in different categories by the source digital database.

all the relevant articles from this particular database, though the same query yielded more articles from the other database. Because we looked up the databases manually against the final sample set of articles, more articles showed up for each database than it could itself return. This indicates that the individual search engines matters in performing queries in addition to the specific query string.

4. Discussion

The main aim of this paper is to update on the state-of-the-art in smartphone medical apps' research. The goal is to highlight the trends of research work on this topic. This survey differs from many previous reviews in its recentness, and its focus on the literature on apps rather than the apps themselves. It also contributes a proposed taxonomy of the related literature.

Developing a taxonomy of the literature in a research area, especially an emerging one, can bring several benefits. On the one hand, a taxonomy of the published works imposes a sort of organization on the mass of publications. For example, a new researcher to the trend of mHealth apps can feel overwhelmed with the sheer number of papers written on the subject without any kind of structure, and fail to draw a proper sense of the actual activities in this area. Numerous articles address the topic from an introductory perspective, others examine a selected number of existing apps, and some might contribute real apps to the field. A taxonomy of the related literature

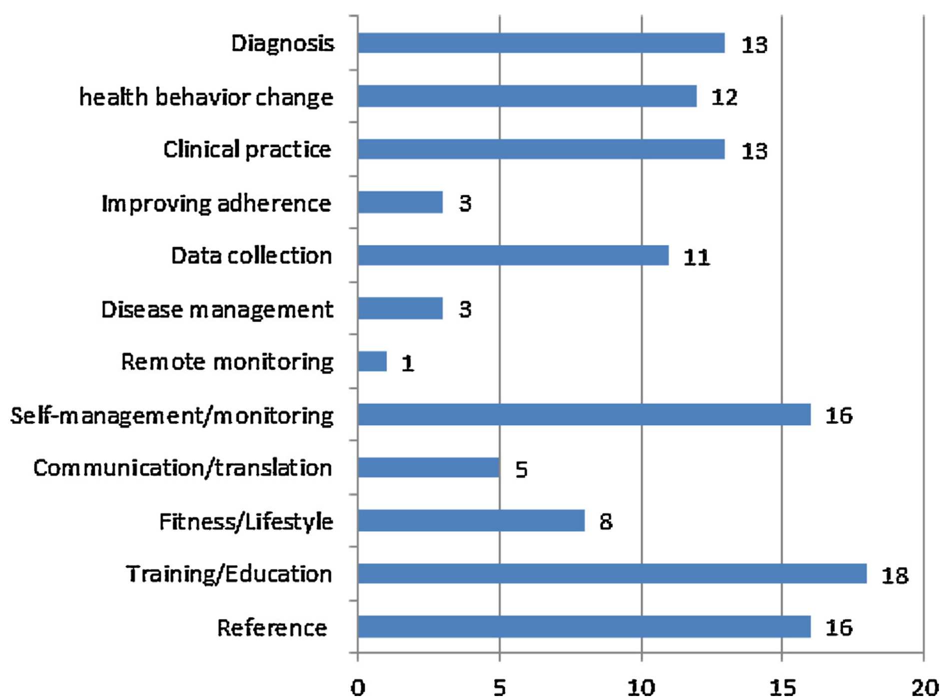

Fig. 5 – Number of included articles by the purpose or function of apps they cover.

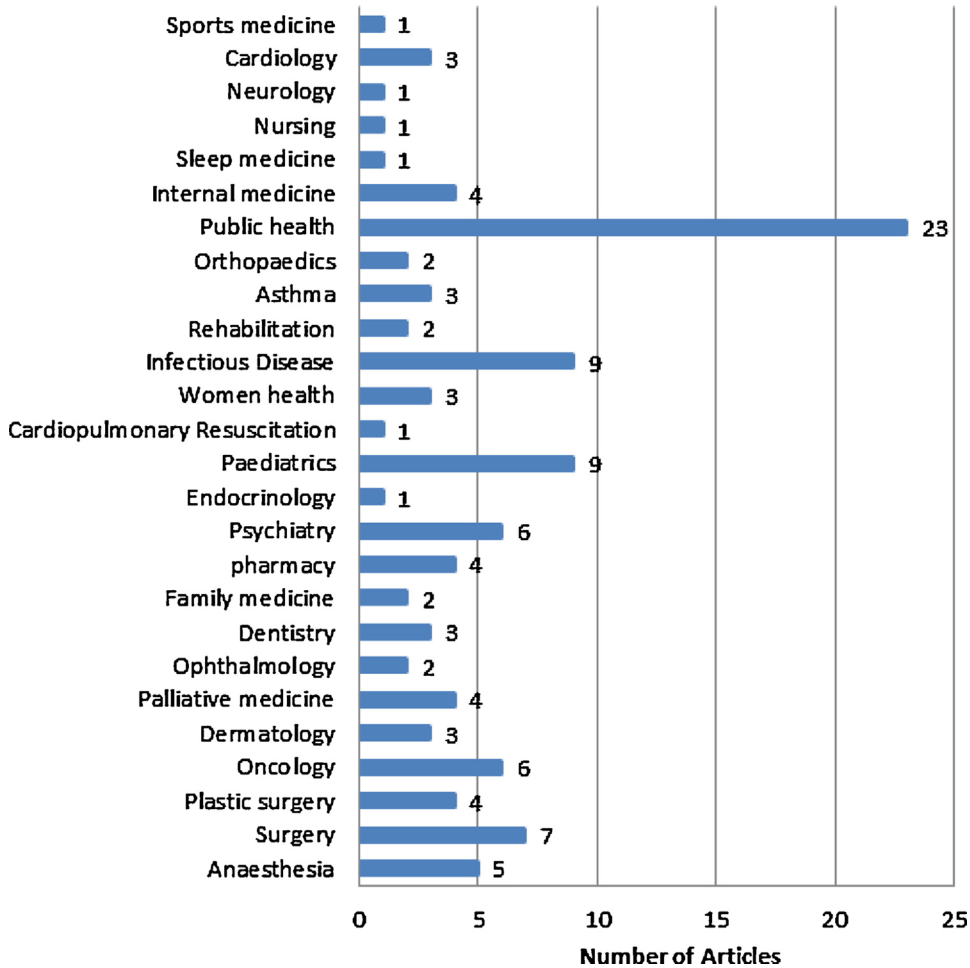

Fig. 6 – Number of included articles by the specialty of apps they cover.

helps to sort out those different works and activities into a meaningful, manageable and coherent layout. On the other hand, the very structure introduced by the taxonomy provides all researchers with important insights into the subject field in several ways. First, it outlines the potential directions of research in the field. For example, the taxonomy of mHealth apps in this work shows that researchers are interested in informing their peers as well as the public of the available apps in a certain specialty or for a particular disease; and that this is a possible path to contribute in this area. Other paths include the assessment of current apps or sharing the experience of developing actual apps. Another type of insight that a taxonomy can provide is to reveal the gaps in the available treatments of the subject. Mapping the works on smartphone medical apps into distinct categories highlights the weak and strong spots in terms of research coverage. For example, the taxonomy in this article shows how groups of individual apps are receiving the major attention in terms of review and evaluation (reflected from the proliferation of their categories), at the expense of more integrated solutions and frameworks as well as more development efforts. Combined with the survey on adequate and representative sample of the literature, this taxonomy also highlights the lack of studies on non-functional aspects of the apps, such as security and privacy aspects, which have received considerable attention in the literature on more traditional eHealth technologies. In addition, the statistics on individual categories of the taxonomy points out the active sectors in medical care in coping up with the new mHealth trend and the less active areas. Finally, similar to taxonomies in other fields, if the researchers in this area adopted certain taxonomy and referred to it frequently, a common language is developed among them to communicate and discuss new works. We can talk, for example, about a development paper, a comparative study, a specialty-based review and so on when referring to works on smartphone medical apps.

Based on the surveyed works, the following sections present three aspects of the literature content; namely, the motivations behind involving smartphone apps in healthcare, the challenges to the successful utilization of this technology and the recommendations to alleviate such difficulties.

4.1. *Motivations*

The benefits of using smartphone apps in the healthcare domain are obvious and compelling. This section lists but a few of the advantages reported in the literature, grouped into categories of similar benefits and citing the corresponding references for further discussion.

4.1.1. *Benefits related to smartphones agility/portability*

Smartphones are agile, handheld, and can be used on the move [116]. This mobility and portability allow for several benefits. For example, Smartphone apps can provide timely communication [34], and are ideal for keeping a symptom diary as they accompany users all the time [23]. From a research perspective, smartphone apps allow conducting ecological momentary assessment (EMA) using MAs, where patients can capture data describing their experience on spot in real time [22], and they also allow for repeated sampling of behaviour over numerous time points and allow the ability to capture less frequent and rare events [101].

4.1.2. *Benefits related to smartphones' capabilities/features*

As mentioned earlier in the introduction, smartphones possess several capabilities that enable new possibilities via installed apps. Because they can connect to the Internet, smartphones are useful to keep clinicians up-to-date with the latest medical techniques and advances [116]. The continuous connectedness of smartphones allows the sharing of behavioural and health data with health professionals or peers [75]. This ability may also allow telemedicine to replace time-consuming office visits altogether [6]. Moreover, Smartphone medical apps are specifically created to work well for point-of-care decisions about topics such as drug dosing and conventional treatment regimens, where the needed information are aggregated and presented in an easily digestible format [77]. The increasing ability of smartphones to use internal sensors to infer context such as user location, movement, emotion, and social engagement has raised the prospect of continuous and automated tracking of health-related behaviours and timely, tailored interventions for specific contexts [75]. Apart from hardware or software features, the feature of anonymity granted by apps allows patients to ask questions they might otherwise feel embarrassed asking a healthcare professional [22].

4.1.3. *Benefits related to smartphones' market penetration*

The popularity and ubiquity of smartphones allow for access into populations that are difficult to reach and engage [36]. For patients who cannot access care provision premises, medical apps are especially beneficial [89].

4.2. *Challenges*

Though attractive, smartphone medical apps are (still) not believed to be the panacea of healthcare delivery. The surveyed works indicated that researchers are concerned about many challenges associated with apps and their use in healthcare. Key reported challenges for adoption of medical apps are listed below, along with citations to references in which the reader can find the original suggestion and further discussion on those challenges. The challenges are classified into a few groups according to their nature.

4.2.1. *Concerns on quality*

Perhaps the most persistent and crucial challenges are those related to the quality of the developed medical apps. Major issues include concerns on the low involvement of qualified professional in app development [26], a lack of extrinsic scrutiny and peer review after publishing [26,43,77], lack of evidence of clinical effectiveness, [43], lack of objective research to evaluate outcomes [89], the absence of content regulation [19] as well as the absence of a regulatory framework that standardizes development [89]. Furthermore, many smartphone apps are not based on behavioural change theories or guidelines [6].

4.2.2. *Concerns on security and privacy*

Privacy of patients and security of their data are also a major and pertinent issue when talking about smartphone apps, and has been frequently raised by researchers [6,19,34,89]. Elias et al. note the non-compliance of medical apps with the Health Insurance Portability and Accountability Act, unlike the traditional EHRs [34]. They also notice that the apps distribution business model needs caution. Apps and service provided are free to the individual, but privacy is not assured. Information collected about an individual while using the app and its associated services can then be used for targeted marketing either directly by the company or sold to others for marketing or product development [34]. Furthermore, there are always security risks for less experienced users who might be tricked to download apps that contain malware or offer them dubious medical information and advice [6].

4.2.3. *Concerns on integration*

It is important to note that medical apps are just one (important) aspect of mobile health, which is one form of healthcare delivery; as such, a vital issue is the lack of integration with other parts of the healthcare delivery system [43]. In particular, technical challenges are caused by the lack of seamless interfaces between app platforms and providers' existing information technology systems [89].

4.2.4. *Concerns on usability*

Many researchers also highlighted the problems in using smartphone apps because of the additional involved complexity and the limited usability compared with traditional platforms such as PCs. For example, complexity is introduced to individuals by the need to manage a mix of mobile devices, personal apps, and apps they use for healthcare purposes, each with its own learning curve, possible financial costs, and security and privacy concerns. This burden on consumers could become overwhelming with each organization, provider, and associated businesses requiring use of their own apps [34]. Moreover, those in rural areas may have limited or no signal and will be unable to benefit from the use of medical apps. Beyond access, the patient has to commit to daily use of the app [34]. Other usability issues relate to the small internal storage capacity, processing power and screen size of the mobile phone, which require apps to be used in a reduced format, potentially reducing clarity [19,89]. There are also the prosaic issues such as remembering to recharge a device and the simple maintenance of equipment within a patient's home, which may be problematic [89].

Furthermore, older patients in particular may suffer from lack of knowledge or discomfort with technology [89]; an app that is perfectly usable by a younger person might be very difficult to manipulate by an older or disabled person [6]

4.2.5. *Concerns on safety*

In a medical environment, apps might cause unexpected effects, such as surface contamination. Smartphones can act as a reservoir for bacteria, and it is possible that doctors using medical apps are less likely to perform hand hygiene, thereby increasing the risk of bacterial transmission [19]. Electromagnetic radiation from the mobile devices not only could hamper the functionality of patient devices such as pacemakers, but also could interfere with other medical equipment [128]. In addition, app descriptions in general contain limited advice or safety information regarding their use as a medical tool [43].

4.2.6. *Concerns on financial costs*

Despite the pervasiveness of smartphones, certain cost overhead associated with medical apps might hinder their wide adoption and use. Examples of the cost overhead include the hidden charges of connection, particularly for apps that automatically connect to other apps or services [34]. In addition, some patients cannot afford smartphones or the required high-speed Internet connection. For app providers, the development, support, maintenance and regular updating may entail significant costs [6].

4.2.7. *Concerns on administrative and ethical issues*

A less obvious source of difficulties is the reimbursement obstacles caused by communication via smartphones for providers who devote time to these types of activities [31]. Providers working in fee-for-service environments will generally expect to be paid for the time they spend on managing care through apps and for associated software or equipment costs. Yet insurers, employers, and other payers are unlikely to reimburse for these costs until there is more robust evidence of their effectiveness [89].

In addition, ethical and medico-legal questions arise when smartphones are used to record patient information via medical apps. Informed consent from individual patients would be required [130]. Moreover, advertising through apps allows companies to target physicians directly, potentially indirectly and unethically influencing prescribing and treatment practices [16].

4.2.8. *Concerns on negative effects*

Finally, the use of smartphone apps for medical purposes may entail unwanted effects, many of which have been highlighted in the literature. For example, self-monitoring of certain measures (like glucose) by patients can cause depression and may do more harm than good [23]. Further, apps that provide medical advice based on their own collected data and algorithms could cause unnecessary worry or false reassurance [43]. Other reported challenges include the mistakes and omissions in health care work settings because of distraction and interruptions caused by interaction with apps or their notifications, the impact on inter-professional relationships due to over-reliance on communicating by apps, resulting in a decrease in verbal communication, and unprofessional behaviours in the use of smartphones by residents [128]. Another important issue is the effect on aspects of essential communication between patients and care providers, such as eye contact, gestures, visibility of actions, and verbal and nonverbal contact [128,131].

4.3. *Recommendations*

To complete the picture, we also summarize the most important recommendations in the literature to mitigate the challenges and facilitate the safe and effective use of medical apps by healthcare professionals as well as patients and the public.

4.3.1. *Recommendations to users*

To improve the chances of using apps of better quality and reliability, all users, including patients and physicians are advised to use available assessment services. A notable example is Happtique, a mobile health solutions company that launched its Health App Certification Program, which is a voluntary programme designed to help clinicians and patients easily identify apps that are credible and safe [23]. Patients are also recommended to peruse the reviews found in the apps pages on online stores and to consider sources of the apps before using it [23]. Physicians are encouraged to exchange information with other doctors using a specific app and to have the app tried by a doctor before prescribing it to a patient [23]. From a security perspective, users are advised to ensure that data are encrypted and the smartphone is password-protected before using any app through which private health information can be transmitted or stored [23]. To mitigate contamination risks caused by the use of smartphones, users can consider several measures [128]: the use of sterilized bags for keeping smartphones when entering patient-care and other sensitive zones; the use of gloves while interacting with patient-care and other sensitive zones; and the use of sanitizing wipes and/or hand sanitizers at regular intervals, especially before dealing with patients.

4.3.2. *Recommendations to developers/providers*

Providers of medical apps, including individual developers, are required to adopt evidence-based principles and standards of app development [23] and to involve patients and physicians alike in the app development process [33]. Training can also be necessary in order to help users get the most out of apps, especially in the case of older adults [52]. Developers are also recommended to improve content quality through the same essential measures governing the quality of information on the web, including the provision of authorship information; the medical professional involvement in content preparation; attribution of all references or sources of content; and the disclosure of app sponsorship or other commercial funding arrangements, and any potential conflicts of interest [6]. One notable recommendation is to integrate voice-function capability into all health-related apps that might be used at the workplace in order to reduce distractions of manual interaction with apps [128].

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4.3.3. *Recommendations to health and federation authorities/organizations*

Health authorities and regulatory agencies hold a major responsibility in the support, guidance, and in assuring the quality of medical apps and their application in the delivery of healthcare. Many researchers have laid out several suggestions for health authorities and organizations. The most important recommendations are to regulate medical apps in order to ensure that patient safety is maintained [23], to encourage the involvement of health-care agencies in developing apps [46], and to incorporate medical apps into provider reimbursements schemes and integrate them into EHR systems and other health information technologies [89]. Health authorities are also expected to educate the public on how to identify the few evidence-based apps available publicly [55], and to improve accountability of app content through simple measures, such as to require app providers of full authorship disclosure, listing of regulatory approval, recognized quality assurance standards, and of external reviews [19]. Vendors should also be required to provide information on their products' functionalities and limits. Mandatory information should cover data management, data protection and privacy issues [123]. An ambitious recommendation is to develop a standardized reporting tool for providing unified form of such information on apps [123].

Organizations that adopt medical apps in their practice should perform analyses of the strengths, weaknesses, opportunities, and threats (SWOT) to judge if a smartphone app adds value to their patient care and other services [128], and seek to establish local security and privacy policies for smartphone usage [130]. An interesting recommendation discussed in [83] is to avoid over-regulating medical apps by government health authorities so as to retain their open nature, and manage the regulation process primarily by the healthcare community itself. Obviously, defining the limits of over-regulation needs some consensus, which is still behind the scene now, as the main concern in this stage is to catch up with the surge of circulating apps and impose minimum measures of quality assurance.

4.3.4. *Recommendations to researchers*

Whether a part of the healthcare industry or academia, researchers are expected to conduct research on medical apps, including trials, in order to determine the reliability, efficacy, and usability of apps [55]. Research is also recommended to capture patterns of smartphone use in healthcare education and clinical practice in order to develop and recommend appropriate learning materials and activities for healthcare delivery [131]. A nice endeavour that can be tackled by researchers or dedicated groups is to develop and maintain a regularly updated and readily accessible online database of information on proved medical apps that have been evaluated and/or successfully used by others [96].

A couple of final notes are in order. First, as Fiordelli et al. [3] pointed out, it is possible that many studies on medical apps do exist in the "grey literature", such as consumer magazines, websites, or blogs (e.g., iMedicalApps [144]), making them out of the reach of surveys that refer only to peer-reviewed literature. Second, a pertinent observation is made by Donker et al. [47], where they noted that the competitive and time-consuming process of grant applications and Randomized Control Trial designs (necessary for high-quality research that evaluates medical apps) contrasts with the speed of development in this technology. They proposed to conduct component testing with small sample sizes to help bridge the gap between academia and real-world applications. This is also supported by the note in [108]: the full-blown assessment of some apps via clinical trial or evaluation studies might fall well beyond the resources of a single person or a small team; the general community has to take this into consideration, both with respect to developers of the apps as well as to research groups.

5. Limitations

The most pertinent limitation to this survey is the number and identity of the source databases, though we believe that the selected sources are a good and broad representative collection. Second, the fast progress in this field hardly allows for any timeliness in a survey. Third, we emphasize the fact that a snapshot of research activity on this vital trend of medical apps does not necessarily reflect the reality of apps use or impact, it just reflects the response of the research community to the trend, which happen to be our very objective in this article.

6. Conclusions

A recent disruptive trend in mobile health is the wave of smartphone apps that address medical and health applications. Research on this trend is already active, though its shape and outlines are still not understood, and an insight on what is actually going on in this emerging line is needed at the current stage. This article aimed to contribute such an insight through surveying and taxonomizing the literature. Specific patterns can be drawn from the mass of works on medical apps, roughly classifying the research into four distinct categories: reviews/surveys, research studies on apps, development attempts and broad framework proposals. Some specialties received more attention from researchers (e.g. public health) as well as few functions (e.g. health reference materials). This typically reflects the types of available apps in the wild but gives a clear indication of where are the gaps in apps development and/or evaluation. Researchers have expressed their concerns in the literature, and many suggested recommendations to resolve the existing and anticipated challenges, the list of which opens many opportunities for research in this field. Similar to other emerging technologies, most of the studies initially focus on the functional aspects of the technology (usefulness of medical apps), leaving the non-functional requirements (e.g. their security) to a later stage.

People will continue to adopt new technologies as they appear; therefore, for researchers to keep abreast of this race, they ought to look at the next thing. The next thing in mHealth seems to be the wearable gadgets connected to smartphones, managed by apps and enabled by the new wave of built-in biosensors. As of this point, no research is found on apps that control wearable devices or embedded biosensors; calling for

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an important line of research that might intersect with several other technological and scientific lines.

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Conflicts of interest

None.

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