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Review article

An ontology of and roadmap for mHealth research

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ABSTRACT

Purpose: Mobile health or mHealth research has been growing exponentially in recent years. However, the research on mHealth has been ad-hoc and selective without a clear definition of the mHealth domain. Without a roadmap for research we may not realize the full potential of mHealth. In this paper, we present an ontological framework to define the mHealth domain and illuminate a roadmap.
Methods: We present an ontology of mHealth. The ontology is developed by systematically deconstructing the domain into its primary dimensions and elements. We map the extent research on mHealth in 2014 onto the ontology and highlight the bright, light, and blind/blank spots which represent the emphasis of mHealth research.
Findings: The emphases of mHealth research in 2014 are very uneven. There are a few bright spots and many light spots. The research predominantly focuses on individuals' use of mobile devices and applications to capture or obtain health-related data mostly to improve quality of care through mobile intervention.
Conclusions: We argue that the emphases can be balanced in the roadmap for mHealth research. The ontological mapping plays an integral role in developing and maintaining the roadmap which can be updated periodically to continuously assess and guide mHealth research.

1. Introduction

Mobility is central to the notion of participatory healthcare. It provides freedom from temporal and spatial constraints to both providers and recipients of healthcare, and thus facilitates their participation in healthcare. Not surprisingly, the domain of mobile health, or mHealth as it is commonly denoted, has garnered much attention in recent years as its application has come to permeate the healthcare industry. The concept of mobility has evolved from the physical transportation of healthcare staff and equipment to simply transporting information using modern technologies [1]; a novel paradigm that begins in telemedicine and telehealth [2], giving rise to the concept of eHealth with mHealth as its subset [3]. The smartphones and associated technologies represent the next stage of the evolution in 'transporting information to transform healthcare' [4], and consequently mobility of and participation in healthcare.

There has been an explosion of research on mHealth in the last few years. There are altogether 808 mHealth articles with abstracts indexed in PubMed between 2013 and January 2015 when the data was collected, of which 364 (45%) are from 2014. Similarly, the number of mHealth articles indexed in Scopus has seen an exponential increase since 2010 [1]. The numbers are likely to grow unabated.

Research on mHealth has been selective, largely focusing on the mobile applications or apps, based on several reviews of the domain. "Most studies narrowly focused on text messaging systems for patient behavior change, and few studies examined the health systems strengthening aspects of mHealth." [5] This statement aptly reflects the narrow focus of the mainstream mHealth research. The domain of mHealth however transcends mobile applications or text messaging. It stands at the crossroads of information and communication technologies (ICT) and patient- and outcome-oriented healthcare. Regardless, the landscape of mHealth research is scattered with narrowly-focused research niches. Most studies emphasize behavior change, intervention, or self-monitoring for adherence to treatment or medication [6–12] while others focus on adoption or specific characteristics of mobile applications [13–20]. A few others examine the use of mobile

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technologies in prevention, diagnosis, treatment, patient care, and education in general [21–24].

Amidst this rapid explosion of interest, the definition of the mHealth domain remains unclear. Researchers have focused selectively on different parts of the whole, neglecting the 'big picture'. This selectivity results in fragmentation of the research agenda; the sum of the parts simply falls short of making the whole. There is a need to articulate and make the combinatorial complexity of mHealth visible to facilitate effective research on mHealth systems [25]. "The current confusion in the nomenclature and classification hinder telemedicine research ... it frustrates our efforts to reach a reasonable understanding of what we already know and what we need to know. Equally important, it impedes progress toward development and implementation of a research agenda geared toward reaching answers to questions regarding the true benefits and costs of telemedicine." [26,p. 492] With these concerns in mind, we use an ontology to frame and represent the complexity of mHealth. The ontology can be used both prospectively to construct a roadmap to guide research and retrospectively to map and assess present research in the domain. The ontology and the mapping can be updated periodically to refresh the roadmap.

We will first review some key definitions of mHealth and then logically deconstruct the concept using an ontology. We will then describe how the ontology can be used to define the domain of mHealth, and how it can be extended, reduced, refined, and coarsened to adapt to the evolving technology and environment for healthcare. Last, we will delineate how the ontology can be used to map the state-of-the-research and the state-of-the-practice in mHealth, discover the gaps in research and between research and practice, and formulate a strategy to bridge those gaps and generate synergy—all with the goal of making the whole greater than the sum of its parts.

1.1. Definitions of mHealth

The term mHealth and its variant m-Health date back nearly twenty years, a period that has seen their definition shift within both the landscape of health technologies and the discipline to which they were applied. The definitions suggest the dimensions and elements of the mHealth domain but do not comprehensively denote the domain. We will present and discuss these definitions, and in the next section draw upon them to construct an ontology of mHealth.

Istepanian, Jovanov and Zhang [27] define mHealth [they spell it m-Health] as "mobile computing, medical sensor, and communications technologies for healthcare." As the title of their article suggests, they envision it leading to "...seamless mobility and global wireless health-care connectivity." In a more recent article they suggest the "...*evolution of m-health towards targeted personalized medical systems with adaptable functionalities and compatibility with the future 4G networks*." [28,italics in the original] Their definition focuses on the hardware and networks driving the transition, and the potential impact on healthcare in general due to enhanced connectivity. It is a technology-based definition.

Akter, D'Ambra and Ray [29] define "mHealth... as the use of mobile communications such as PDAs and mobile phones for health services and information. Researchers have recently extended the definition of mHealth by focusing on any wireless technologies (e.g., Bluetooth, GSM, GPRS/3G, Wi-Fi, WiMAX) to transmit various health-related data content and services through mobile devices, including mobile phones, smartphones, PDAs, laptops and Tablet PCs." Further, they suggest that the ubiquity of mobile phones "is a central element in the promise of the mobile platform for healthcare." [29] Like the previous, this definition is singularly technology-based.

The World Health Organization affirms the absence of a standardized definition of mHealth [30]. It goes on to use the definition of mHealth as "medical and public health practice supported by mobile devices, such as mobile phones, patient monitoring devices, personal digital assistants (PDAs), and other wireless devices... [It] involves the use and capitalization on a mobile phone's core utility of voice and short messaging service (SMS) as well as more complex functionalities and applications including general packet radio service (GPRS), third and fourth generation mobile telecommunications (3G and 4G systems), global positioning system (GPS), and Bluetooth technology." [30] Speciale and Freytsis [31] use the same definition in their call to action for midwives. This definition too is primarily anchored on technology with reference to both medical and public health practice instead of healthcare in general; the two healthcare areas have different stakeholders and information management needs.

Nacinovich [3] defines mHealth as a subsection of eHealth. It is "the use of mobile communications for health information and services... to improve health outcomes." This definition does not focus on the technology but on health information, services, and the outcomes the technology may enable. It complements the earlier definitions.

In contrast to the above definitions, Bashshur, Shannon, Krupinski and Grigsby [26] hierarchically deconstruct mHealth (they refer to it as m-Health) as a component of the ICT (Information and Communication Technology) health domain. Within this domain, they portray the progression from Telemedicine to Telehealth to eHealth (or e-Health) to mHealth. They propose four components of the mHealth domain: clinical support, health worker support, remote data collection, and helpline [26]. They further suggest functionality, applications, and technology as the three basic dimensions of any telehealth (including mHealth) system. Each dimension has many components.

It is understandable that many of the definitions are driven by the 'm' for mobile technology. The technology is the catalyst. Yet the technology must be embedded in a mobile system for healthcare to be effective. These definitions do not embody a systemic view of the information system in which the technology is embedded, nor do they explicitly include the participation of stakeholders and the final outcomes of the healthcare system for which it is intended. They do not capture the combinatorial complexity of the domain. The definition proposed by Bashshur, Shannon, Krupinski and Grigsby [26] comes closest to doing so, but it too suffers from the type of selectivity bias that risks skewing the design of the system and undermining its effectiveness. Using definitions such as those illustrated, designers and users may fail to see the 'big picture'—they may develop excellent technological solutions but whose effect on healthcare is unpredictable. In the next section, we logically deconstruct mHealth and define its domain using an ontological framework.

1.2. Ontology of mHealth

It is difficult to effectively present the full complexity of mHealth using a linear natural English narrative. Such a narrative would be too voluminous and increase the risk of selectivity in its research and application. On the other hand, a structured natural English representation using an ontology can be parsimonious and effective in capturing the complexity of mHealth, while making it visible and comprehensible. The ontology is a combinatorial, visual, natural English representation, which can also be translated into other languages. In this section, we present an ontology of mHealth.

An ontology represents the conceptualization of a domain [32]; it organizes the terminologies and taxonomies of the domain. It is an "explicit specification of a conceptualization," [33,p. 908] and can be used to systematize the description of a complex system

[34]. “Our acceptance of an ontology is... similar in principle to our acceptance of a scientific theory, say a system of physics; we adopt, at least insofar as we are reasonable, the simplest conceptual scheme into which the disordered fragments of raw experience can be fitted and arranged.” [35,p. 16] Using an ontology we make the metaphorical ‘elephant’ visible.

An ontology of mHealth is shown in Fig. 1. Four illustrative components of mHealth derived from the ontology are listed below the ontology, each with an example. A glossary of all the terms is given in Appendix A. We will discuss the construction of the ontology, its dimensions, taxonomies, elements, and the components encapsulated within.

Our method of constructing an ontology is explained by Ramaprasad and Syn [25,36]. It was iterative amongst the authors of the paper (a physician in training and two information systems professors) and by the authors with the extent literature. The challenge was to construct an ontology which is logical, parsimonious, and complete. It had to be logical in the deconstruction of the domain, parsimonious yet complete in the representation of the domain. It had to be a closed description of the mHealth domain.

The challenge was also to adapt the information system terminology to mHealth. This was done by iterating with the literature and creating a glossary of terms (Appendix A). In this context, we should note that the ontology presented is one of many possible ontologies of the mHealth domain. A complex domain like mHealth can be studied from many points of view, each with its own ontology. It is a ‘wicked’ [37] problem with many potential formulations. Each ontology can be a lens by which one may study the domain—ours is one of many possible lenses.

The mHealth ontology is detailed in Cameron, Ramaprasad and Syn [1]. The ontology deconstructs the domain of mHealth into three dimensions: mHealth System, Stakeholders in the healthcare system, and Outcomes of the healthcare system. (Note: Words which refer to the dimensions and sub-dimensions of the ontology are capitalized. We will also capitalize references to elements of a dimension—its categories and subcategories.) The dimensions are represented by columns or a concatenation of columns in Figure 1. The definitions of mHealth discussed earlier include these dimensions implicitly; we have explicated them in the ontology. The mHealth System is the system built around the mobile technology to manage healthcare information. The Stakeholders are those with a stake in the delivery/receipt of healthcare whose role includes the associated management of information using mobile technology. The Outcomes are the desired results of healthcare sought through the meaningful use of mobile technology for the management of healthcare information, extending the concept of meaningful use of healthcare information systems [38,39]. In other words, the outcomes of a mHealth system are a function of the mHealth system and stakeholders.

$$\mathrm{OutcomesofmHealthSystem} = f(\mathrm{mHealthSystem}, \mathrm{Stakeholders})$$

The ontology further deconstructs the mHealth System into three sub-dimensions: Structure, Function, and Semiotics. The Structure defines the physical and organizational objects constituting the system; the Function defines the actions of the system; and the Semiotics the information objects managed by the system. The structural/functional deconstruction is widely used in analysis of physical, biological, and logical systems. The explicit identification of the Semiotics dimension recognizes the centrality of management of the morphology, syntax, semantics, and pragmatics of information [40] in mHealth.

$$\mathrm{mHealthSystem} \subset [\mathrm{Structure}, \mathrm{Function}, \mathrm{Semiotic}]$$

A two-level taxonomy of elements articulates each dimension. These taxonomies can be extended by adding more elements, reduced by deleting elements, refined by adding more levels, and coarsened by aggregating existing levels. The elements and the number of levels in the taxonomy define the scale and granularity of the dimension.

The first-level taxonomy of Structure is based on the common body of knowledge in information systems [41]. The structure of an information system is commonly described in terms of Hardware, Software, Networks, data, Processes, people and Policies. To limit the redundancy of elements, we have excluded data and people from this level given their inclusion as fundamental components of the Stakeholder and Semiotics dimensions respectively.

The second-level elements are specific to mHealth. Thus, Sensors and Devices are the focus of mHealth Hardware; Platforms and Applications are the focus of Software; Local Wireless and Telecommunication networks are the focus of Networks; Manual and Automated processes are the focus of Processes; and, Privacy and Regulation are the focus of Policies. The five categories and the ten subcategories define the elements of Structure for performing the Functions of mHealth described next.

$$\begin{aligned}\mathrm{Structure} \subset [&\mathrm{Hardware}(\mathrm{Sensors}, \mathrm{Devices}), \mathrm{Software}(\mathrm{Platform}, \\ &\mathrm{Applications}), \mathrm{Networks}(\mathrm{LocalWireless}, \mathrm{Telecommunication}), \\ &\mathrm{Processes}(\mathrm{Manual}, \mathrm{Automated}), \mathrm{Policies}(\mathrm{Privacy}, \mathrm{Regulation})]\end{aligned}$$

We started with the commonly used taxonomy of information system Functions: acquisition, storage, retrieval, processing, and distribution. These functions are relevant to mHealth but do not fit well with the focus of mHealth in research and practice. Hence, we modified the first-level taxonomy of Functions to include: Acquisition, Storage, Analysis, Interpretation, Application, and Deletion/Erasure. The modified taxonomy overlaps and extends the common taxonomy.

The second-level elements are particular to mHealth, as with the second-level elements of Structure. Thus, Storage can be Encrypted or Non-Encrypted; Analysis can be Quantitative or Qualitative; Interpretation can be Diagnostic, Predictive, or Interventional; Application can be Adoptive, Prescriptive, Scholastic, or Distributive; and Deletion/Erasure can be Local or Systemic.

$$\begin{aligned}\mathrm{Function} \subset [&\mathrm{Acquisition}, \mathrm{Storage}(\mathrm{Encrypted}, \mathrm{Non\text{-}Encrypted}), \\ &\mathrm{Analysis}(\mathrm{Quantitative}, \mathrm{Qualitative}), \mathrm{Interpretation}(\mathrm{Diagnostic}, \\ &\mathrm{Predictive}, \mathrm{Interventional}), \mathrm{Application}(\mathrm{Adoptive}, \mathrm{Prescriptive}, \\ &\mathrm{Scholastic}, \mathrm{Distributive}), \mathrm{Deletion/Erasure}(\mathrm{Local}, \mathrm{Systemic})]\end{aligned}$$

Here we use the variant of the traditional taxonomy of data, information, and knowledge which is commonly used in the information systems literature. Data is defined as raw facts and figures, information as summarized or processed data, and knowledge as learned or applied information [41,42]. We substitute information with Health Records and keep Data and Knowledge. These correspond to the morphological, syntactic, and semantic levels [40] of semiotics. It must be noted that there is no element corresponding to the pragmatic level. Often, wisdom is included as the final element after knowledge [43]. We have chosen not to include it for many reasons. Despite its attractiveness, the concept of wisdom continues to be a far less tangible concept than data, information, and knowledge. It is difficult to identify, let alone use information technology (including mHealth) to acquire, store, analyze, interpret, apply, and delete/erase. The hardware, software, networks, processes, and policies for managing wisdom too have not been articulated in the literature. Perhaps in the future when wisdom management systems become available, Wisdom could be added to the Semiotics taxonomy.

mHealth System

Structure	[for mobile]	Function	[of]	Semiotics	[by]	Stakeholder	[to meaningfully manage]	Outcome	[of/in healthcare]
Hardware		Acquisition		Data		Healthcare Providers		Efficiency	
Sensors		Storage		Static		Physicians		Cost	
Devices		Encrypted		Streaming		Nurses		Time	
Software		Non-Encrypted		Health Records		Pharmacists		Resource	
Platform		Analysis		Current		Care Teams		Quality	
Applications		Quantitative		Historical		Organizations		Standard	
Networks		Qualitative		Knowledge		Hospitals/Clinics		Accuracy	
Local Wireless		Interpretation		Current		Government/		Efficacy	
Telecommunication		Diagnostic		Traditional		Health Agencies		Safety	
Processes		Predictive				Insurers		Parity	
Manual		Interventional				General Population			
Automated		Application				Individuals			
Policies		Adoptive				Families/Groups			
Privacy		Prescriptive				Communities			
Regulation		Scholastic							
		Distributive							
		Deletion/Erasure							
		Local							
		Systemic							

Illustrative components:

Software for mobile interpretation of data by general population to meaningfully manage quality of

Example: Applications for tracking/flagging health data (e.g., fitness, blood pressure, glucose, etc.).

Software for mobile application of knowledge by healthcare providers to meaningfully manage quality of healthcare.

Example: Clinical decision-support tools promoting adherence to evidence-based guidelines (e.g., e-checklist, UpToDate, etc.).

Networks for mobile application of knowledge by healthcare providers to meaningfully manage efficiency of healthcare.

Example: Real-time communications tools between providers (e.g., text-based, voice-based, cloud-based, etc.).

Hardware for mobile acquisition of data by healthcare providers to meaningfully manage efficiency of healthcare.

Example: Wireless Data Acquisition Module (WDAM) for continuous monitoring of patient data derived from wearable sensors.

Example: Bluetooth-embedded mobile devices for remote data transmission (vitals, GPS coordinated, etc.)

Software for mobile interpretation of health record by general population to meaningfully manage safety of healthcare.

Example: Personal Health Records (PHRs), Applications providing medical support/health information tools for general population (e.g., WebMD, MedicineNet, Healthline)

Policies for mobile application of knowledge by organizations to meaningfully manage quality of healthcare.

Example: Government regulatory control (e.g., FDA safety and innovation act), mHealth Regulatory Coalition guidelines.

Processes $_{\text{manual}}$ for mobile deletion $_{\text{local}}$ of data $_{\text{static}}$ by healthcare providers $_{\text{physicians}}$ to meaningfully manage safety in healthcare.

Example: Default expiration dates for patient data downloaded/entered/stored on mobile devices.

Fig. 1. An Ontology of mHealth.

The second-level elements are again customized to mHealth. Thus, Data can be Static or Streaming; Health Records can be Current or Historical; and Knowledge can be Current or Traditional.

$$\text{Semiotics} \subset [\text{Data}(\text{Static}, \text{Streaming}), \text{HealthRecords}(\text{Current}, \text{Historical}), \text{Knowledge}(\text{Current}, \text{Traditional})]$$

The mHealth System is defined by the combination of elements from its Structure, Function, and Semiotics. It includes, for example: (a) hardware for mobile acquisition of data (for example, a smartphone); (b) software $_{\text{applications}}$ for mobile interpretation of health records $_{\text{current}}$ (for example, a decision support app); and (c) policies $_{\text{privacy}}$ for mobile deletion/erasure of data $_{\text{static}}$ (for example, policies for storing patient data on personal devices). (Note: Second-level elements are shown as subscripts.) The ontology encapsulates 90 potential first-level components of the mHealth System and 780 potential second-level components. These components constitute a complete, closed description of a mHealth system.

There are three broad stakeholders in the mHealth System. They are: (a) the Healthcare Providers, (b) the healthcare Organizations, and (c) the General Population who receive healthcare. The Healthcare Providers include the Physicians, Nurses, Pharmacists, and Care Teams. The Organizations include Hospitals/Clinics, Government/Health Agencies, and Insurers. The General Population includes Individuals, Families/Groups, and Communities.

A mHealth system may cater to the selective needs of a subset of stakeholders. Continuing with the three illustrative components of a mHealth system, one may think of: (a) hardware for mobile acquisition of data for healthcare providers $_{\text{physicians}}$; (b) software $_{\text{applications}}$ for mobile interpretation of health records $_{\text{current}}$ for general population $_{\text{individuals}}$; and (c) policies $_{\text{privacy}}$ for mobile deletion/erasure of data $_{\text{static}}$ for organizations $_{\text{hospitals/clinics}}$. Each of the 90 potential first-level components and the 780 potential second-level components of mHealth may be concatenated with the Stakeholder groups or subgroups to enumerate the potential requirements of mHealth for the stakeholders. It will be a very large number. In designing a mHealth system one will have to be selective.

$$\text{Stakeholders} \subset [\text{HealthcareProviders(Physicians, Nurses, Pharmacists, CareTeams), Organizations(Hospitals/Clinics, Government/HealthAgencies, Insurers), GeneralPopulation (Individuals, Families/Groups, Communities)}]$$

Efficiency, Quality, Safety, and Parity of healthcare are the dominant concerns of healthcare information systems, at least in the USA [38,39]. They define the meaningful use of healthcare information systems. It would be appropriate to seek the same outcomes for mHealth systems. Efficiency may be measured in terms of the Cost, Time, and other Resources utilized by stakeholders in the delivery of healthcare, which constitute the second-level elements. Similarly, quality may be measured in terms of the adherence to Standards, Accuracy of diagnosis and treatment, and the overall Efficacy of care. Extending the illustration of the three components of a mHealth system one may consider the following three components of mHealth: (a) hardware for mobile acquisition of data for healthcare providers $_{\text{physicians}}$ to meaningfully manage safety in healthcare; (b) software $_{\text{applications}}$ for mobile interpretation of health records $_{\text{current}}$ for general population $_{\text{individuals}}$ to meaningfully manage efficiency $_{\text{cost}}$ of healthcare; and (c) policies $_{\text{privacy}}$ for mobile deletion/erasure of data $_{\text{static}}$ for organizations $_{\text{hospitals/clinics}}$ to meaningfully manage quality $_{\text{standard}}$ of healthcare.

$$\text{Outcome} \subset [\text{Efficiency(Cost, Time, Resource), Quality(Standard, Accuracy, Efficacy), Safety, Parity}]$$

1.3. Components of mHealth

The dimensions (and sub-dimensions) of the ontology are arranged left to right with adjacent words/phrases with a purpose. The concatenation of an element from each dimension with the adjacent words/phrases creates a natural English sentence illustrating a potential component of mHealth. The concatenation has been demonstrated with the three examples carried through the discussion of the dimensions of the ontology as well as the four illustrative components with examples listed below the ontology.

At the most detailed level, the ontology encapsulates 67,200 potential components of mHealth. For an aggregate view, one may consider only the first-level of the taxonomies. The components and fragments (of these components) define the domain of mHealth. It would be laborious and voluminous to enumerate all the components. The ontology provides a convenient and concise 'big picture' of mHealth. It helps visualize the combinatorial complexity of the domain.

It may be possible to instantiate a component in many ways. Consider the first example above: hardware for mobile acquisition of data for healthcare providers $_{\text{physicians}}$ to meaningfully manage safety in healthcare. Instantiations may vary in terms of the hardware used, data acquired, and safety criterion addressed. The same logic can be extended to the other examples.

A particular mHealth research or application may instantiate only a small number of components encapsulated in the ontology. Further, some components may be instantiated frequently and some infrequently. We will call those frequently instantiated as 'bright' spots, those infrequently instantiated as 'light' spots, and those uninstantiated as 'blind/blank' spots. A component may be 'bright' because of its relative value to the field and/or ease of study/implementation; it may be 'light' due to its lack of value and/or difficulty for study/implementation; it may be 'blind' if it has been overlooked; or, it may be 'blank' due to infeasibility of study. By mapping the state-of-the-research and the state-of-the-practice onto the ontology one can discover the 'bright', 'light', and 'blind/blank' spots in each, thereby demonstrating deficiencies existing both between and among research and practice. Further, since the possible explanations for the luminosity of a component is equivocal, one must dig deeper to find the underlying cause. An important 'bright' spot would be functional but an easy one would be dysfunctional. Similarly, an unimportant 'light' spot may be acceptable but a difficult, highly valued 'light' spot may be unacceptable. Last, a 'blind' spot has to be investigated deeper lest it be important, and a 'blank' spot clearly demarcated so as not to waste one's effort. In the next section we will discuss how the ontology can be used as a lens to study the topography of mHealth research [44].

2. Methods

Though the earliest article on mHealth dates back to the 1976 (based on a search in PubMed) in the field of telemedicine, the majority of research has come about only in the past few years beginning circa 2010. mHealth research has evolved with the evolution of the technology to support mobility. The confluence of (a) rapid evolution of the General Population as participants rather than simply recipients of healthcare, (b) widespread adoption of healthcare information systems, and (c) dramatic advances in mobile technologies is fundamentally altering the topography of mHealth research. We mapped all articles on mHealth published in 2014 and indexed by PubMed to portray the recent state-of-the-research—its 'bright', 'light', and 'blind/blank' spots.

We searched PubMed in January 2015 for all journal articles using the search string: mHealth [Title/Abstract] OR "mobile health" [Title/Abstract] OR "mobile healthcare" [Title/Abstract] OR ("delivery of health care" [MeSH Terms] AND ("wireless technology" [MeSH Terms] OR "cellular phone" [MeSH Terms] OR "mobile applications" [MeSH Terms])). The search string was developed through a number of iterations. Our objective was to be inclusive in obtaining the population of relevant articles in mHealth research. The search yielded a total of 1820 articles (excluding those without an abstract), out of which 364 are from 2014. These 364 articles were mapped onto to the ontology as described below.

We downloaded the title and abstract of the articles into an Excel tool developed by one of the authors to aid coding. Using the tool, a coder can map each article, based on its title and abstract, to the elements of the ontology the article addresses. Only elements which are explicitly addressed are coded; elements which are implicitly addressed or could be expected to be addressed in a particular context are not coded. For example, one may expect that almost all mHealth systems will have some form of Storage. However, if the Storage Function is not mentioned in the title or abstract, it is not coded. Thus, the coders tried to minimize both over-coding (including elements not explicitly present) and under-coding (excluding elements explicitly present).

First, the articles were coded by one of the authors (an information systems professor). Then, another author (a physician in training) reviewed and modified the initial coding. A comparison matrix was developed to determine the similarities and differences between the two coders. Last, the first coder reviewed the differences and finalized the revised coding. The final coding is the consensus between the two coders. We sought to assure the reliability of coding through this three-stage iterative process with feedback.

An article may instantiate multiple components, a component, parts of multiple components (fragments), or part of a component (fragment) of the ontology. There is no restriction on how many elements of the ontology could be encoded with reference to an article, or a requirement that an article should be encoded with reference to all the dimensions of the ontology. Thus, an article can be encoded to: (a) an element from each dimension, (b) multiple elements from each dimension, (c) an element from some dimensions, or (d) multiple elements from some dimensions.

The coding is binary—whether the element (or its synonym) is present or not in the title and abstract. The coding is not weighted; each article and each element was assigned equal weight.

The data were analyzed using the same Excel tool used for coding to generate an ontological map of the mHealth research domain monads—the frequency of occurrence of each element (monad) in the ontology. The population (and not a sample) of articles from 2014 was mapped onto the ontology. Hence the reliability of the mapping for that year is completely a function of the reliability of the coding. There can be no sampling bias for the year, except due to potential errors in exclusion and inclusion of articles. This map is presented and discussed in the section below.

3. Results

The ontological map of monads in research papers on mHealth published in 2014 is shown in Fig. 2. The number in parentheses adjacent to each dimension is the number of articles out of 364 encoded on that dimension. The number adjacent to the element is the frequency of its occurrence in the corpus. The bar below the element is a visual representation of the same scaled to the maximum frequency (in this case 219 out of 364 for Software-Applications). We note that the number of articles encoded on a dimension may be greater than the sum of the encoding of the elements in the dimension, due to multiple coding of articles on a dimension.

The monad map is very uneven. There are two 'blind/blank' spots: Deletion/Erasure-Local and Deletion/Erasure-Systemic. Thus, almost all the monads in the ontology are instantiated in the research. In other words, the 2014 corpus covers the mHealth domain defined by the ontology almost completely. There are also a few 'bright' spots and many 'light' spots in each dimension. The distinction is subjective and visual.

Among the 364 articles, 285 are coded on Structure—it is a significant dimension. The dominant focus of the research in terms of mHealth Structure is on Software-Applications (219) and Hardware-Devices (109). This reflects the dominant focus on the use of apps and smartphones. These may be called the 'bright' spots. Among the rest, the focus on Hardware-Sensors (28) is the highest. This reflects the focus on use of smartphone based sensors. There is very little (but some) focus on Software-Platform, Network-Local Wireless and Telecommunication, Processes-Manual and Automated, and Policy-Privacy and Regulation. These may be called the 'light' spots.

Among the 364 articles, 271 are coded on Function—it is a significant dimension. The dominant focus of the research in terms of mHealth Functions is, in descending order, on Interpretation-Interventional (126), Acquisition (108), Application-Distributive (81), and Application-Adoptive (74). Storage, Analysis, and other forms of Interpretation have been given very little attention. A large number of the studies focus on use of smartphones, mobile phones, apps, and SMS to assure adherence to a treatment regimen by acquiring data, interpreting it and intervening when necessary, translating the interpretation into action, and distributing the recommendation to the appropriate stakeholders.

Among the 364 articles, only 186, about half, are coded on Semiotics—it is a less significant dimension in the corpus. The dominant focus of research in terms of mHealth Semiotics is, in order of significance, on Data-Static (82), Knowledge-Traditional (57), Knowledge-Current (45), Data-Streaming (39), and Health Records-Current and Historical (25 each). This reflects a focus on acquiring data (usually through smartphone and mobile phones) and translating it into knowledge for action. The intermediate step of organizing the data in electronic health records and extracting information is less emphasized.

Among the 364 articles, 231 are coded on Stakeholders—it is a significant dimension. Within these, the dominant focus is on the General Population-Individuals (169). There is some focus on Healthcare Providers-Physicians (42) and Healthcare Providers-Care Teams (24). And, there is a smattering of focus on the other Healthcare Providers (Nurses (11) and Pharmacists (2)), Organizations (Hospitals/Clinics (9), Government/Health Agencies (12), and Insurers (1)), and members of the General Population (Families/Groups (10), and Communities (4)). The focus is individual-based recipients and providers—while narrow, is understandable given the ubiquitous use of smartphones and mobile phones which are primarily individual-based devices.

Among the 364 articles, 203 are coded on Outcome—it is a less significant dimension, particularly so from the perspective of participatory health information systems. The very dominant Outcome of concern is Quality-Efficacy (133)—perhaps a necessary first step for smartphone apps before moving to the other objectives. The other outcomes studied are, in order, Efficiency-Cost (31), Parity (29), Efficiency-Time (22), Quality-Accuracy (18), Safety (17), Efficiency-Resource (15), and Quality-Standard (8). Much of this research addresses the question of how these other objectives can be achieved using mHealth.

Thus, the ontological map of monads summarizes the topical coverage of the population of mHealth research articles indexed by PubMed in 2014, through the lens of the ontology. In the next sec-

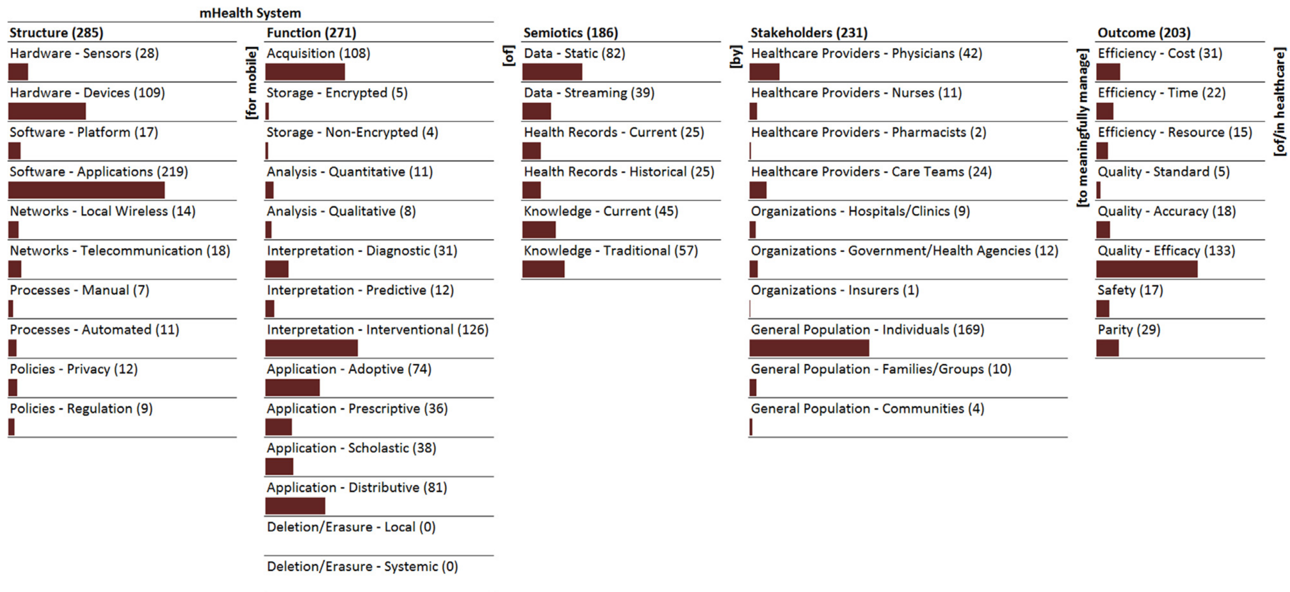

Fig. 2. Ontological Map of 2014 mHealth Research Monads.

tion, we will discuss these results with a view to develop a roadmap for mHealth research.

4. Discussion

The ontology of mHealth (Fig. 1) is a complete, closed representation of the system. It represents mHealth's combinatorial complexity, systematically and parsimoniously. The ontological map (Fig. 2) of 2014 mHealth research is a comprehensive mapping of the corpus on to the ontology. As we have summarized earlier, there are a few 'bright' spots in the map, many 'light' spots, and a couple 'blind/blank' spots. Overall, while the coverage of the corpus with reference to the ontology is extensive, the variation in luminosity among the elements within a dimension and across dimensions is high. Thus, the corpus of 2014 research on mHealth is selective and not systemic. In the following we will discuss the selective and a systemic emphasis in each of the five dimensions of the ontology, and its implications for participatory health information systems. We will start from the right and move left.

The four Outcomes—Efficiency, Quality, Safety, and Parity are all important for the meaningful use of any healthcare system, including a mHealth system. Their relative priority may vary by context. The heavy emphasis on Quality-Efficacy may be natural and necessary in the early stages of mHealth development, but ultimately the domain has to ensure a balance between Efficiency, Quality, Safety, and Parity of mHealth-based care. It is a good sign that there is some research on each of the outcomes in the corpus; it indicates recognition of their importance. Yet, Safety is the focus of the fewest (17) articles. The highly selective emphasis on Quality-Efficacy may be detrimental to the advancement of mHealth systems. It may be an easy and convenient starting point, but the focus has to be expanded and balanced to attain meaningful use of mHealth in participatory health information systems. The potentials for Efficiency and Parity are significant drivers of mHealth in such systems. They need to be studied more.

All the Stakeholders are participants in the mHealth system. The success of providing healthcare via mHealth to the General Population—Individuals (169) by Healthcare Providers-Physicians (42)—the two dominantly emphasized in the corpus—will depend upon the inclusion and the performance of many of the other Stakeholders. Moreover, each of the Stakeholders, individually and interactively, is likely to be concerned with using mHealth for improving Efficiency, Quality, Safety, and Parity. The corpus minimally recognizes all the stakeholders (at least in one article). Again, the two focuses may be easy and convenient starting points but the corpus has to expand and balance the coverage if mHealth is to transform healthcare, and an integral part of participatory health information systems.

Interestingly, the emphasis in Semiotics is heavier at the extremes (Data and Knowledge) and less in the middle (Health Records—information). Comparatively, the emphases among the Semiotics categories are more balanced than in all the other dimensions. The corpus clearly recognizes all the Semiotics elements. The centrality of Health Records in the future may require greater study of its role in mHealth too. The records, after all, are the anchor of meaningful use of participatory healthcare information systems. Further, semiotics is the currency of participation. Relative to the total number of papers (364) the number focusing on semiotics is low (186). Effective participation in healthcare information systems via mHealth will require a significantly increased emphasis of research on this dimension.

In terms of the Functions, the emphasis on Interpretation, Acquisition, and Application is understandable. And, so is perhaps the lack of emphasis on Analysis at the early stage of development of mHealth systems. However, given the importance of HIPAA (in the US) and similar laws in other countries it would be difficult to explain the lack of emphasis on Storage (Encrypted and Non-Encrypted) and Deletion (Local and Systemic). The effects of this lacuna will be exacerbated in participatory healthcare information systems. Assurance of privacy and security through these functions will be critical to encouraging participation. Lack of trust in the system will diminish participation. The taxonomy of Function is ordinal—Acquisition precedes Storage, Storage preceded Analysis, Analysis preceded Interpretation, Interpretation preceded Application, and Application preceded Deletion. A systemic approach had to have a balanced emphasis on all stages—Storage, Analysis, and Deletion in mHealth have to be addressed better by the research corpus.

The emphasis on the mHealth Structure elements is very highly skewed. It is biased towards the technology and fails to address the infrastructure (Networks) and soft (Processes and Policies) issues necessary to be addressed in the design of an effective mHealth system. Processes and Policies have been shown to be the Achilles heel in the implementation of information systems in general—mHealth systems are unlikely to be an exception. Successful participation in healthcare information systems using mobile technologies will depend on the deployment of the full spectrum of structural elements in the ontology.

Further, a relatively light focus on Sensors suggests that mHealth research has been playing catch-up with the growing trend and research in Internet of Things (IoT) [45,46] which refers to "the networked interconnections of everyday objects" [47]. Such objects can include devices and sensors that constitute the body area networks (BAN) or networks of interconnected body area sensors to enable ubiquitous healthcare [48]. These networks are integral to real-time mobile healthcare [27,28,49] regardless of many challenges and issues [50,51]. Yet the emphasis on this area in the overall scheme of mHealth research seems to be surprisingly negligible.

Thus, overall, there are significant gaps in the coverage of the mHealth research corpus of 2014. Since it constitutes a significant portion of the entire mHealth corpus, the gaps are strongly indicative of those in the entire corpus. The lag time in research and its publication can sometimes exceed a year and therefore limit the year-to-year variations. Hence, our findings will be valid despite the lag in its publication. The mapping could be revisited in a few years; it should then reveal any changes to the gaps in mHealth research.

The gaps are unlikely due to sampling bias. We have mapped all the articles from the year. While it is likely for the focus of the corpus to have changed over time, it is unlikely that the gaps evident in the 2014 corpus will have been addressed earlier. One may also argue the choice of PubMed itself as a source of sampling bias. It is possible that PubMed has not or does not index some of the articles which address the gaps in the ontological map. Yet, PubMed is a broadly accepted, curated database in healthcare. The choice of PubMed may have introduced some errors of omission, but these errors are likely to be small compared to the scale of the gaps in the ontological map. The articles from other sources can be mapped in the future.

Last, there are no norms about what the relative emphases on the elements should be. While the ontological map in Fig. 2 is visibly skewed, it would be difficult to specify what it should look like. Moreover, the norm or specification may change with new technologies, requirements, regulations, etc. It has to be a context-specific, subjective assessment—but yet systematic and systemic. The ontology, by making visible the core logic of the system, can help articulate both the errors of omission and of commission in the research corpus. Such a discussion will help assess and articulate a roadmap for mHealth research for participatory healthcare information systems.

5. Conclusion

The ontology itself (Fig. 1), by making the logic of mHealth explicit and visible, can serve as a roadmap for research on the topic. It can be used to define the focus and priorities of research. In a sense, each component or fragment (part of a component) encapsulated in the ontology can be the object of research. Defining the research topics using the ontology also has the advantage of making it easy to integrate the results. One will be able to visualize how the parts fit to form a whole.

The present ontology can be refined by adding additional categories and subcategories to the taxonomies. It can also be coarsened by combining the categories and subcategories of the taxonomies. Thus, the ontology as a roadmap is adaptable—it can be adapted to the changing needs of and developments in the domain. For example, in the future it may be necessary to add a Robot with artificial intelligence as a Provider. The addition would be easy because the ontology is modular. A single addition like that would also increase the components encapsulated in the ontology by a very large number. One has to be careful in adding elements to balance the validity of the ontology with its parsimony. Adding an element like the Robot will also immediately pose questions for research, for example: How will it contribute to the Outcomes? What will be its Semiotic capabilities? How will the Structure and Functions of the mHealth System need to be reconfigured?

While the ontology itself (Fig. 1) presents a plain roadmap, the ontological map (Fig. 2) presents the topography of the domain based on the research corpus. The topography, and the reasons for the same, has to be explicated and considered to develop an effective roadmap. The topography of the corpus of 2014 research on mHealth may be due to the: (a) importance of the topic, (b) ease of doing research on the topic, (c) history/stage of research on the topic, and (d) the interaction of the three. The ontological map of monads (Fig. 2) highlights how much each element is emphasized in the corpus. It does not explain why. It is important to explore the reasons in formulating a roadmap for mHealth research.

A frequently researched topic like the use of smartphones and apps to assure adherence may be important, but it may also be simply easy, convenient, and overemphasized. The profusion of studies on this topic to the exclusion of the others highlighted by the ontology raises the possibility of a herd effect driven by the relative ease and convenience of doing research on the topic. It would be for the gatekeepers of the domain to answer the question whether a topic is important because it is frequently researched (and hence frequently cited); or, whether it is frequently researched and cited because it is important. The ontology and the associated map make it convenient to pose these questions.

At the other extreme, using the ontology and associated maps similar questions can be posed about the 'blind/blank' spots. Is the absence of focus on Deletion due to oversight or infeasibility? A patient's right for Deletion and modification are built into the HIPAA requirements while there too it has been rarely researched despite its essential role in ensuring the integrity of a healthcare record. (Integrity along with confidentiality and availability is a cornerstone of HIPAA.) Research on the topic may be difficult but feasible, and necessary in the age of the 'right to be forgotten'. The ontology and the associated maps make it convenient to pose these difficult but important questions.

Author contributions

Joshua D. Cameron: developing the mHealth ontology; determining search keywords; mapping mHealth articles onto the ontology; reviewing ontological mappings; writing and reviewing the paper.

Arkalgud Ramaprasad: developing the mHealth ontology; determining search keywords; mapping mHealth articles onto the ontology; analyzing the ontological maps; writing and reviewing the paper.

Thant Syn: developing the mHealth ontology; defining the search keywords; mapping mHealth articles onto the ontology; reviewing ontological mappings; generating ontological maps; writing and reviewing the paper.

Conflict of interest form

There is no conflict of interest in this research.

Appendix A.

Summary Points

- Mobility is central to the notion of participatory healthcare.
- Mobile health or mHealth research has been growing exponentially in recent years.
- mHealth has been ad-hoc and selective without a clear definition of the mHealth domain.
- mHealth can be systematically and systemically defined by using an ontological framework.
- The emphases of mHealth research in 2014 are very uneven with many lightly emphasized areas but few heavily emphasized ones.
- Ontological maps can help balance the emphases in the roadmap for mHealth research.

Glossary:

mHealth System: Mobile health system used to meaningfully manage healthcare.
Structure: The structural elements of a mHealth system – the nouns describing the system.
Hardware: The physical elements of the mHealth system.
Sensors: Hardware used to measure and input a variety of data for healthcare.
Devices: Hardware used to perform a variety of other information management functions in healthcare.
Software: Computer programs used to manage healthcare information.
Platform: The foundation for software such as an operating system.
Application: Software used to perform a variety of other information management functions in healthcare.
Networks: Wired and wireless connections for transfer of information.
Local Wireless: Wireless networks with limited range, confined to a facility.
Telecommunication: Wired and wireless connections with virtually unlimited range.
Processes: Processes used by the stakeholders to manage information.
Manual: Processes handled almost entirely by people.
Automated: Processes handled almost entirely by computers.
Policies: Stakeholder rules guiding the management of information.
Privacy: Policies regarding privacy of information.
Regulation: Policies regulating the management of information.
Function: The functions of the mHealth system – the verbs describing the behavior of the system.
Acquisition: The function of obtaining information.
Storage: The function of storing information.
Encrypted: Storing the information with encryption to limit its readability.
Non-Encrypted: Storing the information as is, without encryption, and hence directly readable.
Analysis: Processing the information to discover relationships within.
Quantitative: Processing of numerical information.
Qualitative: Processing of non-numerical information.
Interpretation: Discovering the meaning of relationships within the information.
Diagnostic: The meaning of relationships for diagnosis.
Predictive: The meaning of relationships for prediction.
Interventional: The meaning of relationships for guiding intervention.
Application: The use of the interpreted information.
Adoptive: Translating the interpretation into action.
Prescriptive: Prescribing action based on the interpretation.
Scholastic: Using the interpretation for study or further analysis.
Distributive: Propagating the interpretation to others.
Deletion/Erasure: Removal of the information.
Local: Removal of the information locally on a device.
Systemic: Removal of the information everywhere.
Semiotics: The transformation of symbols constituting the information.
Data: The raw symbols – numerical, textual, graphical, etc.
Static: Time invariant data, acquired and stored.
Streaming: Time variant data, acquired in real time.
Health Records: Organization of data to render healthcare.
Current: Record of the current health data.
Historical: Record of historical health data.
Knowledge: Understanding of the logic of health and healthcare.
Current: Current, on-the-point knowledge about health and/or healthcare.
Traditional: Commonly accepted or evidence-based knowledge about health and/or healthcare.
Stakeholder: Entity with a stake in healthcare.
Healthcare Providers: Providers of healthcare.
Physicians: Doctors in clinics and hospitals.
Nurses: Nursing staff in clinics and hospitals.
Pharmacists: Preparers/dispensers of pharmaceutical products in clinics, hospitals, and pharmacies.
Care Teams: Teams of providers.
Organizations: Organizational entities involved in the provision of healthcare.
Hospitals/Clinics: Facilities of in-patient, out-patient, urgent, and ambulatory care.
Government/Health Agencies: Entities regulating and providing auxiliary healthcare services.
Insurers: Organizations providing insurance to healthcare recipients.
General Population: The general recipients of healthcare.
Individuals: Individual recipients of healthcare.
Families/Groups: Recipient families or collections of individuals sharing some activity, interest or quality.
Communities: Communities receiving healthcare.
Outcome: The outcomes of healthcare.
Efficiency: The efficiency of healthcare delivery.
Cost: The cost efficiency of healthcare delivery.
Time: The time efficiency of healthcare delivery.
Resource: The efficiency in terms of other resources like space, people, material, etc.
Quality: The quality of healthcare.
Standard: Quality of adherence to standards.
Accuracy: The accuracy of diagnosis, treatment, etc. in healthcare.
Efficacy: The success of care.
Safety: The safety of recipients and providers of healthcare.
Parity: The parity of healthcare delivered by the providers to the recipients.

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