



Smartphone-based systems for physical rehabilitation applications: A systematic review

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ABSTRACT

Tele-(remote) rehabilitation is attracting increased attention from society, including the research community and commercial marketplace with an estimated global market value of \$160 billion. Meanwhile, mobile device-based healthcare (“mHealth”) has appeared as a revolutionary approach to tele-rehabilitation practice. This paper presents a systematic review of the literature on smartphone-based systems designed for remote facilitation of physical rehabilitation. A total of 74 documents from Web of Science search results were reviewed. Systems were classified based on target medical conditions, and a taxonomy of technology was created along with identification of monitored activities. Beyond monitoring, some systems also provide patient-caregiver communication and progress management functions. The review identifies major research interests in stroke, cardiac disease, balance impairment and joint/limb rehabilitation; however, there is a lack of attention to other diseases. There are also few systems that have computerized existing clinical tests. On the basis of the review, design recommendations are formulated to encourage implementation of advanced functionalities, usability considerations, and system validation based on clinical evidence. Results of this study may help researchers and companies to design functions and interactions of smartphone-based rehabilitation systems or to select technology.

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Introduction

Rehabilitation is the process, performed after an injury, illness or surgery, by which a subject recovers his/her strength, relearns skills or find new ways of doing activities. There are several types of rehabilitation, such as physical, occupational, or speech-language therapies (Shadgan, Roig, Hajghanbari, & Reid, 2010). The present review is focused on smartphone-based systems for physical rehabilitation.

Expensive clinical visits and long duration treatment sessions have been recognized as inherent limitations of traditional physical rehabilitation programs (Dobkin, 2017). Research also indicates that more frequent but shorter intervals of exercise and motor skill training in daily environments may be more effective than the duration of individual clinical sessions (Dobkin, 2017). Tele-rehabilitation, meaning remote delivery of rehabilitation services (Lai, Woo, Hui, & Chan, 2004), offers an alternative solution to the traditional programs. Remotely monitored programs, supervised by health-care professionals, can help patients to develop exercise behavior in real-world environments that remain accessible beyond the duration of in-clinic rehabilitation process (Rawstorn, Gant, Meads, Warren, & Maddison, 2016). Consequently, the interest in the development of telerehabilitation systems is increasing.

According to the Market Research Report in 2017 (QYResearch Group, 2017), the size of the global telerehabilitation market was estimated at \$160 billion, with a growth rate of 27% per year. At the same time, Goldman Sachs identified the total value of the US telerehabilitation market to be \$32.4 billion, with 45% for patient monitoring systems, 37% for telehealth, and 18% for behavioral modification (Goldman Sachs Report, 2016).

The popularity of smartphones also provides opportunities for tele-rehabilitation. Smartphone ownership rate across the world is generally high, especially with advanced economies such as South Korea (95%), Israel (88%), Netherlands (87%), Sweden (86%), Australia (81%), U.S. (81%), and Spain (80%) (Pew Research Center, 2019). The rate varies in emerging economies such as South Africa (60%), Mexico (52%), and Indian (24%). Mobile Health (“mHealth”), has appeared as a revolution for improving individual health and well-being by continuously monitoring a subject’s status (such as blood pressure, gait, fall risk, etc.) and behavior and delivering “just-in-time” interventions through the user’s natural mobile environment (Kumar, Nilsen, Pavel, & Srivastava, 2013). Embedded sensors in smartphones (e.g., inertial measurement units (IMUs), GPS, barometer or camera) along

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with wearable technology can provide enormous information on a person's health status and behavior patterns (Kumar et al., 2013). However, review articles in the tele-rehabilitation area typically cover a wider range of systems and have overlooked the unique characteristics of smartphone-based applications (Peretti, Amenta, Tayebati, Nittari, & Mahdi, 2017).

In this study, we aimed to identify the status of research on smartphone-based systems for physical rehabilitation applications. Thus, we conducted a literature review in the Web of Science (WoS) database and analyzed technology use and maturity of these systems. The results of the review include identification of future research challenges and recommended directions of research. We also formulated some design guidelines for the development of smartphone-based systems that address health-care demands.

Method

The WoS database is a major publication search engine. It facilitates reference of journal publications and citations over a wide range of subjects and often serves as a basis for tenure, promotion and other professional decisions (Hodge & Lacasse, 2011; Seipel, 2003). For this literature search, we used the following search query in WoS for publications on smartphone applications for physical rehabilitation:

$TS = ((\textit{rehabilitation} \textit{OR} \textit{physical therapy} \textit{OR} \textit{physiotherapy}) \textit{AND} \textit{smartphone})$

The initial search was performed in Summer 2017. We reviewed all "hits" for relevance based on titles and abstracts. Only documents in English were reviewed and counted. Subsequently, we read full texts to further assess article relevance. Only those documents meeting the following inclusion criteria were selected for review and analysis: (1) the document describes the development or evaluation of a smartphone-based system for physical rehabilitation; and (2) the smartphone serves as a data acquisition unit, signal processing unit or user interface of the system. We did not apply restrictions based on the timing of publication of research. We excluded studies that: (1) were not related to physical conditions, such as depression, dyslexia, affective disorders, etc.; (2) focused on technical aspects of activity recognition, without application rehabilitation intervention or condition assessment, (3) only presented research protocols without system information, and (4) reviews, notes or letters. Conference proceedings and student theses were included in the review in order to cover the maximum number of executed projects.

The majority of reviewed studies were categorized according to targeted medical conditions, including (among other

Table 1. Definition of maturity levels.

Level	Definition
1	Application concept and design formulation
2	Proof of concept with key technological functions
3	Demonstration of integrated system with full functionality
4	Effectiveness testing with general population or in controlled environment
5	Effectiveness testing or clinical trial with targeted user in intended use environment

categories) stroke, cardiac disease, and joint/limb rehabilitation. Some studies did not specify particular medical conditions and the technology appeared applicable for treatment of a wide range of diseases. Consequently, these studies were categorized as "general physical rehabilitation". The smartphone-based rehabilitation systems identified through our search showed different levels of technological "maturity", including early design concepts to integrated device testing in clinical trials. In order to understand the system maturity levels presented in the literature, We reviewed the Technology Readiness Levels Scale defined by the Department of Defense (DOD; Graettinger, Garcia, Sivi, Schenk, & Syckle, 2002), the stages of research framework (SORF) defined by the National Institute on Disability, Independent Living, and Rehabilitation Research (National Institute on Disability, Independent Living, and Rehabilitation Research, 2017) as well as the telemedicine evaluation framework, proposed by Jansen-Kosterink, Vollenbroek-Hutten, and Hermens (2016). However, these scale descriptions are hardly applicable or are only indirectly relevant to the systems that we reviewed. Therefore, we identified five levels of technological maturity (similar to military "technology readiness levels") as a basis for classifying systems, with level 1 being the lowest level of maturity (as shown in Table 1). The maturity levels were defined by following the conventions of the above two references.

A few other studies revealed through the search attempted to computerize traditional clinical tests using smartphone systems. Different from systems that target medical conditions, these technologies are designed to be used in clinics by physical therapists as a replacement for traditional assessment methods. Although such systems are not intended for tele-rehabilitation, they do represent an additional type of smartphone-based application for physical therapy. Consequently, computerized clinical tests were analyzed and discussed separately.

Results

Article selection

The initial search returned 209 hits from WoS of which 74 documents were included for further review and analysis.

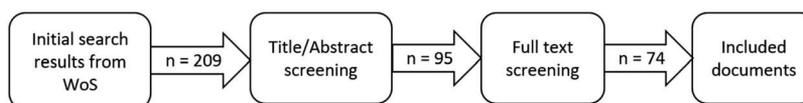


Figure 1. Documents selection process.

Figure 1 shows our selection process. The reviewed documents included 40 journal publications (~54%), 33 conference proceedings (~45%), and 1 student thesis (~1 %).

The distribution of studies across the period 2010–2017 is presented in Figure 2. The plot reveals exponential growth in the number of studies in this area and reflects increasing interest in the research community. The earliest study we found was published in 2010 and the year 2016 appears to have been the most productive to date. The lower number of studies in 2017 is due to the timing of our search at the middle of the year.

Review results

A summary of the characteristics of the studies targeting medical conditions is presented in Table 2. Technologies employed in these rehabilitation systems included both smartphone-based sensors and body-mounted devices (e.g., wearable sensors). The responses or outcomes monitored by each system are also identified in the table. Based on the summary data, a maturity level was assigned to each system, according to the degree of development and validation work presented in the related studies.

In order to better understand the development status of smartphone-based rehabilitation systems, the first year of a publication occurring in each category (i.e., type of medical condition) was recorded in Table 3. The means and standard deviations of the maturity level of the technologies addressing each condition or test category were also calculated.

The studies focusing on computerization of clinical tests are summarized in Table 4. Technologies used in these systems were identified and classified as smartphone-based and body-mounted sensors. Studies typically presented complete system designs and assessed intra-rater and/or inter-rater reliability in use, measurement error, and output correlation with traditional test results. Most studies concluded “good to excellent reliability” (based on inter- and intra-class correlations (ICCs)) or “high accuracy” (based on standard error of measurement or discrepancies from gold-standard tests), and recommended clinical application of the smartphone-based test alternatives.

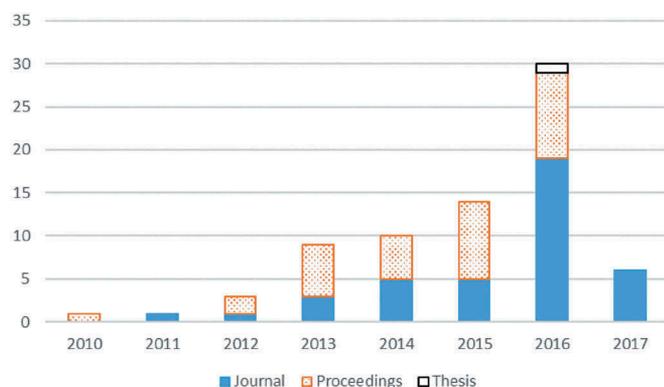


Figure 2. Number of studies by year of publication.

Discussion

Publication status

In general, the search results revealed a significant increase in studies of smartphone-based rehabilitation systems over the past decade. Other telemedicine literature has made the observation that a higher percentage of systems have been presented through conference proceedings (Şenel & Demir, 2015; Yang et al., 2015). According to our review, this was true for the years before 2016. However, the number of journal publications in this area significantly increased in 2016. It is likely that researchers have chosen to introduce system design and preliminary testing through conference proceedings prior to more complete submissions for journal publication. An example is the system *iJoint*, which was presented in two proceedings (Ongvisatepaiboon, Chan, & Vanijja, 2015a; Ongvisatepaiboon, Vanijja, & Chan, 2015b) before a journal publication (Ongvisatepaiboon, Vanijja, Chignell, Mekhora, & Chan, 2016).

Smartphone-based rehabilitation systems for medical conditions

Most of the smartphone-based systems covered in this review (~84%) were focused on rehabilitation for specific medical conditions. Chronic diseases attract more attention because the effectiveness of long-term rehabilitation is limited by a lack of patient adherence to protocols and high costs for frequent clinical visits (health.gov, n.d.). Furthermore, the prevalence of multiple chronic conditions is high, specifically 42% in the U.S. These diseases affect a broad population and result in higher healthcare service costs (Buttorff, Ruder, & Bauman, 2017). For example, North Americans with five or more chronic conditions spend 14 times more on health services than people without chronic conditions. Improvement of patient lifestyle and monitoring general physical activity, such as step counts, are common approaches to support at-home recovery from chronic diseases. IMUs are the most frequently used sensors, either alone or in combination with other types of sensors, such as EMG and heart rate monitors. IMUs are typically used to measure posture or motion, which appear to be the most frequently monitored activities. In the following paragraphs, we further discuss the technology used in tele-rehabilitation applications and activities and/or responses monitored by the smartphone-based applications for different medical conditions. Most of these medical conditions result in temporary or permanent physical disabilities.

Stroke

Stroke appears to be the most common health condition for application of smartphone-based rehabilitation, probably due to the large affected population (Choi, Ku, Lim, Kim, & Paik, 2016; Guo et al., 2015). Research (Patel et al., 2006) suggested prevalence of disability and handicap up to 3 years after stroke. Most stroke patients suffer from mobility loss and require long-term intervention to re-establish psychomotor abilities (Lee et al., 2014). Systems in this category mostly

Table 3. Review summary by category.

Category	Total # of studies	Earliest Publication	Maturity Level (Mean \pm SD)	% of High Maturity (Level 4 or 5)
Stroke	11	2010	3.4 \pm 0.9	27%
Joint/Limb Rehab	10	2012	3.5 \pm 1.0	40%
Balance/Stability Impairment	9	2013	3.3 \pm 0.9	56%
Cardiac Disease	9	2011	3.9 \pm 1.5	56%
Parkinson	5	2014	4.2 \pm 1.1	60%
Respiratory	3	2016	3.7 \pm 1.2	33%
Arthritis	1	2016	3	0%
Cerebral Palsy	1	2013	2	0%
Chronic Pain	1	2016	4	100%
Diabetes	1	2017	5	100%
Exoskeleton Training	1	2015	4	100%
Traumatic Brain Injury	1	2015	2	0%
General Physical Rehabilitation	10	2012	3.3 \pm 0.8	33%

monitor posture or motion of patients during rehabilitation and motor training. For example, Lee et al. (2014) used body-mounted IMU sensors to measure upper-extremity range of motion during sensorimotor recovery exercises. Other studies also explored gait behavior monitoring (Edgar, Swyka, Fulk, & Sazonov, 2010; How, Chee, Wan, & Mihailidis, 2013), fall detection (Allen et al., 2013) and cardiac responses (Farjadian, Sivak, & Mavroidis, 2013). In terms of technology, while a few systems (Guo et al., 2015; How et al., 2013; Shin & Song, 2016) have made use of IMU sensors embedded in smartphones, more systems (Brueckner, Theimer, & Blume, 2014; Ciou et al., 2017; Edgar et al., 2010; Farjadian et al., 2013; Lee et al., 2014; Wang et al., 2016) have integrated

external sensors for data acquisition and make use of the smartphone as a data processing unit. It is interesting to note that some systems have integrated sensors into garments (e.g., insoles, shirts, gloves) to facilitate continuous monitoring of daily activity (Edgar et al., 2010; Farjadian et al., 2013; Wang et al., 2016). However, smart garment systems reveal lower levels of technological maturity, as compared to systems based on regular IMU sensors. Most smart garment studies were at the stage of system development, rather than testing the effectiveness of systems on controlling patient disease state. A few smartphone-based games (Choi et al., 2016; Ciou et al., 2017; Guo et al., 2015; Shin & Song, 2016) have been developed to increase patient motivation for training and ultimately increase the time committed to rehabilitation. Preliminary testing of these game applications has shown high acceptance and adherence rates as well as positive patient feedback (Choi et al., 2016; Ciou et al., 2017; Guo et al., 2015; Shin & Song, 2016).

Balance/stability impairment

Balance/stability impairment is a form of disability that can be caused by various diseases (e.g., Gill-Body, Beninato, & Krebs, 2000; Tyson, Hanley, Chillala, Selley, & Tallis, 2006) or injuries (Konradsen, 2002; Riemann & Guskiewicz, 2000). A number of smartphone-based rehabilitation applications have been developed to help patients regain stability and balance control during movement. IMU sensors are the only type of sensors that have been applied (to date) by systems in this category. Aside from Lee and Fung (2015) that used an external IMU sensor, all other systems in this category have used smartphones as data acquisition tools by requiring users

Table 4. Smartphone based computerized clinical tests.

Study	Technology		Clinical Test	# of Participants	Validation Results
	Smartphone-based	Body-mounted			
Pourahmadi et al. (2017)	ACC		Goniometry (wrist ROM)	70	Good to excellent intra-rater and inter-rater reliability (ICCs >0.85) and concurrent validity ($r = 0.85$ and 0.91 for flexion and extension ROM)
Cruz and Morais (2016)	IMU		Upper limb neuro-dynamic test (Elbow extension ROM)	41	Relatively high standard error of measurement with onset of pain, but better results with maximum tolerant point
Pourahmadi et al. (2017)	ACC		Goniometry (lumbar ROM)	30	Good to excellent intra-rater and inter-rater reliability (ICCs > 0.73) for iPhone app
Banos et al. (2015)		IMU EMG	Trunk Endurance test	10	High inter-rater reliability (ICCs > 0.75)
Milanese et al. (2014)	ACC		Goniometry (Knee ROM)	6	High concordance correlation (CCC >0.98)
Mitchell et al. (2014)	IMU		Goniometry (shoulder external rotation ROM)	94	High intra-rater reliability (ICCs > 0.79) and concurrent validity (ICC = 0.93)
Ferriero et al. (2013)	IMU		Goniometry (knee ROM)	37	High inter-rater and intra-rater reliability (ICCs > 0.958), but image processing on smartphone remains technical challenge
Finkbiner et al. (2017)	Camera		Goniometry (knee angle during heel strike)	32	No significant difference between smartphone app and 3D motion capture system, but the agreements were low to moderate (ICCs = 0.447 ~ 0.454)
N. A. Capela et al. (2014)	Camera		6-minute walk	15	Small difference (<0.07 s) between smartphone and gold standard foot strike timing
N. A. Capela et al. (2015)	Camera		2- and 6-minute walk	5	Small difference (0.014 s) between smartphone and gold standard foot strike timing
Chan et al. (2016)	IMU		Functional Mobility assessment: Perform five-time sit-to-stand (FTSTS) and time up-and-go (TUG) tests	32	Excellent measurement consistency with the lab-based reference (ICCs > 0.946)
Perez and Labrador (2016)	IMU		Functional Gait Assessment (FGA) test	0	Only responsiveness and precision of algorithm was evaluated

ICC, Inter- or Intra-class coefficients; CCC, Concordance correlation coefficient.

to attach the phone to their body or a balance board. Most systems in this category monitor body tilt angles in order to understand patient trunk stability. A couple of newer systems monitor joint movement angles as a basis for promoting proprioception (Mourcou, Fleury, Diot, & Vuillerme, 2016; Mourcou, Fleury, Franco, Diot, & Vuillerme, 2015) or joint stability training (Chiu, Tsai, Lin, Hou, & Sung, 2017). In order to assist balance training, several systems have also applied real-time feedback via different sensory modalities. For example, Afzal, Oh, Choi, and Yoon (2016) delivered visual and haptic cues with different magnitudes of intensity and directions of presentation, based on patient trunk tilt angle. It was found that the multimodal biofeedback provided significant assistance in postural control.

Cardiac disease

Similar to the findings of Peretti et al. (2017), our search and review revealed smartphone-based cardiac rehabilitation systems to focus on rehabilitation as a tool for improving patient quality of life and reducing cardiac risk factors, mainly through lifestyle changes. Smartphones are often paired with heart rate monitors such as heart rate belts (Worringham, Rojek, & Stewart, 2011), smartwatches (Busnatu & Sinescu, 2015; Dobrican & Zampunieris, 2016) or integrated bioharnesses (Maddison et al., 2014; Rawstorn et al., 2016). There has also been exploration of other means of heart rate monitoring. Chung et al. (2016) attempted to estimate heart rate using video images of the fingertips taken by a smartphone camera. This technology was expected to eliminate the need for external devices and guide exercise intensity in real-time for patients. However, the estimation accuracy of this approach was limited by motion artifacts and is not at a clinically acceptable level. In addition to heart rate, some applications for cardiac disease-related rehabilitation also monitor respiration activity (Maddison et al., 2014; Rawstorn et al., 2016), blood pressure (Busnatu & Sinescu, 2015) and O₂ saturation level (Busnatu & Sinescu, 2015). To promote patient lifestyle changes, more mature systems record general physical activities, such as step counts (Rawstorn et al., 2016) or walking distance (Maddison et al., 2014; Worringham et al., 2011), and support physician-patient communication for lifestyle guidance. For example, with the application developed by Yudi et al. (2016), physicians can check patient exercise data and provide feedback accordingly. Patients can also receive dietary suggestions and health tips from the application.

Joint/limb rehabilitation

Joint/limb rehabilitation is associated with disabilities caused by injury, operation, or chronic disease, such as osteoarthritis (Jones, Skrepnik, Toselli, & Leroy, 2016) and “frozen shoulder” (Ongvisatepaiboon et al., 2015a, 2015b, 2016). Most smartphone-based joint/limb rehabilitation systems use IMUs (Liu et al., 2016; Ongvisatepaiboon et al., 2015a, 2015b, 2016) or simply accelerometers (Matera, Boonyasirikool, Saggini, Pozzi, & Pegoli, 2016; Ongvisatepaiboon et al., 2015a, 2015b) to monitor body part movements during exercises. Monitored movements include wrist deviation angles (Matera et al., 2016), shoulder rotation (Ongvisatepaiboon

et al., 2015a, 2015b, 2016) and knee extension (Liu et al., 2016), etc. Researchers have also investigated other types of technologies for such applications. Bril et al. (2016) measured gait behavior with IMUs and pressure sensors embedded in shoe soles and provided step counts for lower limb rehabilitation. Bercht, Boisvert, Lowe, Stearns, and Ganz (2012) used EMG signals to classify hand gestures and provide feedback on exercise quality for hand rehabilitation. More mature applications also integrate advanced functions such as progress recording (Matera et al., 2016) and automated motivational messages or reminders (Jones et al., 2016).

Parkinson disease

Parkinson’s disease causes walking disability such as gait and balance deficits, and more specifically freezing of gait (FOG). Consequently, all smartphone applications targeting Parkinson disease rehabilitation are focused on gait performance measurement and FOG detection, usually by placing IMU sensors at the feet of a patient (Casamassima et al., 2014; Ferrari et al., 2016; Ginis et al., 2016; Mazilu et al., 2015) or attaching a smartphone to the trunk of a patient (Pepa, Capecci, Verdini, Ceravolo, & Spalazzi, 2015). Casamassima et al. (2014), Ferrari et al. (2016) and Ginis et al. (2016) presented different research phases of a system named CuPiD. The CuPiD system provides corrective verbal feedback in order to encourage patients to maintain gait parameters within a clinically determined “therapeutic window”. Patients using the CuPiD system demonstrated significant improvements in balance as compared to a control group (Ginis et al., 2016). These features of the system were also appreciated by patients (Ferrari et al., 2016).

Respiratory disease

Research has investigated various strategies for respiratory rehabilitation, including encouraging general physical activity (Vorrink, Kort, Troosters, Zanen, & Lammers, 2016), monitoring respiratory exercise (Pereira, Almeida, & Caixinha, 2016), and gaming (Stafford, Lin, & Xu, 2016). Oximeter (Pereira et al., 2016) and breath belts (Stafford et al., 2016) have been used for real-time breath monitoring, while IMU sensors (Pereira et al., 2016), accelerometers (Vorrink et al., 2016), and GPS devices (Pereira et al., 2016) have been used to monitor general physical activities as part of the same applications. For example, Vorrink et al. (2016) developed an application with rehabilitation goal setting capability, exercise instruction, and remote physician intervention functions. The application represents the most mature technological development in this category of application. Unfortunately, patient testing (to date) has not revealed positive effects of the smartphone-based intervention.

Other clinical conditions and general physical rehabilitation

Few smartphone-based rehabilitation systems documented in the literature have targeted medical conditions other than those described above. We found one study focused on each of arthritis (Nishiguchi et al., 2016), cerebral palsy (Pu et al., 2014), chronic pain (Singh et al., 2016), diabetes (Valentiner et al., 2017) and traumatic brain injury (LeMoyne, Mastroianni, Hessel, &

Nishikawa, 2015) rehabilitation. However, the technologies used for monitoring patient activity remain consistent with the above review of technologies for stroke, balance stability impairment, cardiac rehabilitation, joint/limb rehabilitation, Parkinson's disease, and respiratory rehabilitation. For example, IMU sensors and accelerators are commonly used for posture and motion monitoring (Nishiguchi et al., 2016; Singh et al., 2016) and smart insoles were used to measure gait behavior (Pu et al., 2014). A new approach for other medical conditions is the use of Kinect-based systems to monitor body posture (Singh et al., 2016). There have also been a number of systems developed to monitor general physical activity and they can be applied in the treatment of various diseases. The monitored activities include gait performance (Lin, Wang, Zhuang, Tomita, & Xu, 2016; Redd & Bamberg, 2012; Wagner & Ganz, 2012), posture and motion (Bittel, Bittel, Williams, & Elazzazi, 2017; Bittel, Elazzazi, & Bittel, 2015; Megalingam, Pocklassery, Jayakrishnan, Mourya, & Thulasi, 2014; Wang, 2016; Wang, Chen, & Markopoulos, 2014), step counts (Glynn et al., 2013; Rowlands et al., 2013) and falls (Megalingam et al., 2014). Rather than tailoring functions to specific disease treatment needs, these systems seek to continuously monitor patient activity as a basis for understanding behavior and providing a basis for changes to improve overall health. Related to this, many general physical rehabilitation systems have integrated wearable smart garments, such as smart insoles (Lin et al., 2016; Redd & Bamberg, 2012; Wagner & Ganz, 2012), footpads (Rowlands et al., 2013) and smart jackets (Wang, 2016; Wang et al., 2014). However, all the wearable systems we reviewed were at the level of systems integration vs. more mature development stages.

Smartphone-based computerization of clinical tests

Mobile applications have been developed as computerized versions of various clinical tests. From our review, goniometry, or range of motion (ROM) measurement, has attracted the most research interest due to its importance in clinical assessment, the need for quicker and easier procedures (Pourahmadi et al., 2017) and more portable instruments (Cruz & Morais, 2016). Smartphone-based ROM tests have been developed for many joints, including the knee, shoulder, wrist, and lumbar joints. Although multiple studies have demonstrated good reliability, additional validation tests with pathological populations and larger sample sizes have been identified as a common direction for future work (Cruz & Morais, 2016; Milanese et al., 2014; Mitchell, Gutierrez, Sutton, Morton, & Morgenthaler, 2014; Pourahmadi et al., 2017). Other systems have focused on computerizing trunk endurance tests (Banos et al., 2015), exercise capacity tests (e.g., 2- and 6-minute walking tests; (Capela, Lemaire, & Baddour, 2014, 2015), functional mobility assessment (Chan, Keung, Lui, & Cheung, 2016) and gait assessment tests (Perez & Labrador, 2016). These systems primarily analyze motion or posture by using IMU sensors or image processing with a smartphone camera. Banos et al. (2015) also used wearable EMG sensors to estimate muscle fatigue during tests. Repeated validation testing with different smartphone platforms (Capela et al., 2014) and larger

clinical testbeds (Banos et al., 2015) have been identified as directions of future research for these computerized tests.

Design recommendations

A few design recommendations were formulated based on inspirations from more mature smartphone-based rehabilitation systems presented in the literature. We also consulted classic and contemporary human-computer interaction literature (e.g., Dix, 2009; Molich & Nielsen, 1990) to seek applicable design guidance.

Advanced functionality

The present review covered smartphone-based rehabilitation systems at different stages of development. Beyond patient activity monitoring, the most mature systems offer advanced functions, such as patient progress management and caregiver-patient communication. For instance, Rawstorn et al. (2016) REMOTE-CR platform allows therapists to send exercise prescriptions to a patient, provide coaching, and view patient data throughout exercises. As an example of progress management, MyWalk developed by How et al. (2013) provides users with a summary of progress for each training session and across the duration of therapy. Other systems, such as Vorrink et al. (2016), allow users to set and manage physical activity goals. These additional functions should be considered in the development of future mHealth systems as a means for improving rehabilitation exercise effectiveness, patient confidence, and therapy adherence.

Multimodal feedback

Different sensory modalities should be considered when providing real-time feedback to patients through smartphone-based applications. Using visual feedback, Shin and Song (2016) presented patient trunk movement on a TV, as part of trunk control training, in order to improve task performance. Many systems have also explored auditory and haptic feedback. For example, Liu et al. (2016) used text-to-speech and voice recognition techniques to interact with users through a smartphone application via voice alerts. The current system can caution users to slow down if ROM activities are performed too fast. Shin and Song (2016) used sonification (translation of visual cues to auditory output) tailored to chronic pain patients' psychological and physical capabilities in order to enhance confidence during exercise performance. Related to haptic feedback, Mourcou et al. (2015) used vibrations to alert patients when their trunk movement extended outside a predetermined "dead zone" during balance training. Visual, auditory and haptic modalities have been shown to pose different attention demands in terms of information processing (Rauterberg, 1998), reaction time (Koslover, Gleeson, De Bever, & Provancher, 2012) and use in motor skill training (Clamann & Kaber, 2012). Rehabilitation researchers should carefully choose the feedback modality that is most suitable for the purpose of any system under development, based on the current literature and/or pilot testing.

User-centered considerations

Unfortunately, the present review also revealed a lack of user-centered considerations in the design of smartphone-based rehabilitation systems. As an example, the application of Vorrink et al. (2016) was designed to encourage patient physical activity at home. However, it was shown to be unsuccessful after user testing. Although the reasons remained unclear, the authors believed the lack of a usable interface design caused reduced patient motivation and adherence to physical activity goals. Among the 74 studies that we reviewed, only 20 identified usability considerations with most making use of simple usability surveys of potential users after product design. Furthermore, only two studies proactively applied systematic user-centered approaches in application design. Mazilu et al. (2015) performed participatory design by meeting with clinicians, engineers, and patients, asking prospective users for opinions on system design options, and using user feedback for design refinements. Wang (2016) applied an iterative design approach for designing a posture monitoring garment. She started with low-fidelity prototypes and gradually improved the garment design by upgrading sensors, adding multimodal real-time feedback, and improving fabric patterns through five design iterations.

Usability has been recognized as an important factor for user engagement in systems design (O'Brien & Toms, 2010). One major objective for mHealth systems is to improve patient adherence to rehabilitation programs and promote therapy exercise at home (Matera et al., 2016). This goal cannot be realized without long-term patient engagement with smartphone-based rehabilitation systems. In addition to participatory and iterative design, task analysis (Hackos & Redish, 1998), usability heuristic evaluation (Molich & Nielsen, 1990), and usability testing (Dix, 2009) are other well-established techniques that should be applied by rehabilitation researchers in future mHealth systems design.

Furthermore, accessibility should be another user-centered consideration in designing smartphone-based rehabilitation systems. Many users of such systems may suffer from short-term or long-term disabilities. Improving accessibility in system design will allow patients to complete the treatment with less assistance from family members or health-care providers in applying sensors or following prescribed exercises. With improved accessibility, patients will be able to participate and stay in treatment programs with more independence and engagement.

System validation

With respect to system validation, the percentage of smartphone-based rehabilitation systems that have undergone user testing (i.e., realizing technological maturity levels of 4 or 5) is relatively low. As other studies (Ketchell, 2017; Uscher-Pines et al., 2016; Wu et al., 2017) have demonstrated, there is a clear lack of evidence to support benefits of such systems in terms of treatment results. Most prior efforts in this field have been directed towards establishing sensor accuracy and system functionality rather than determining whether the intervention improves patient health (Wang, 2016). It is important for researchers to encourage collaboration between

technical and clinical teams as a basis for developing and validating future systems with clinical evidence.

Future research directions and challenges

Our review revealed a lack of attention to certain health conditions, including arthritis, chronic pain, and diabetes, in the development of tele-rehabilitation applications. Future research should study mHealth systems for a larger variety of chronic diseases as a potential tool for preventing risk factors and reducing disease complications (de la Torre-Díez, López-Coronado, Vaca, Aguado, & de Castro, 2015; Marzano, Ochoa-Siguencia, & Pellegrino, 2017). Such systems can also facilitate data recording and exchange for caregivers and patients and serve as powerful complements to diagnosis processes. Related to this, new sensors, such as barometers, thermometers, fingerprint sensors, and light sensors, have been incorporated in smartphones in recent years and may support tele-rehabilitation for a broader range of health issues. As an example, barometers can be used effectively for fall detection (Habib et al., 2014), but they have yet to be applied in any smartphone-based rehabilitation system. Researchers should actively explore newly available sensor technologies to broaden patient behavior monitoring capabilities and to support therapy for many health conditions.

Smartphone-based rehabilitation systems bring unique challenges to designers. Many systems are intended to be used by patients at home without the guidance of health-care professionals. This requires an application to present reliable information and to deliver appropriate alerts and advisories, when necessary, in order to ensure medical safety (Kumar et al., 2013). Besides medical safety, engineering safety considerations, such as sensor reliability, are important to prevent unanticipated harm or discomfort to users due to technologies integrated in smartphones (Kumar et al., 2013).

mHealth systems also pose challenges in terms of patient privacy. Many privacy-revealing behaviors such as lifestyle change and movement patterns can now be recorded by smartphone sensors. Furthermore, patient health information is stored on their smartphone or a cloud server, which introduces data security concerns. Designers need to take measures, such as encrypted data transfer and strict access authentication, to guarantee patient safety and privacy before launching a product.

Other challenges include data quality. Signals from ECG or EMG sensors may be inaccurate if the sensors are placed incorrectly or if they become loose or shift location during movement (Kumar et al., 2013). The use of sensors also increases power consumption (Pantelopoulou & Bourbakis, 2010) and the data quality may be degraded if a device needs to conserve battery life (Kumar et al., 2013). Rehabilitation researchers should design alerts of sensor and data integrity faults into future mhealth applications to ensure patients are aware of situations in which application outcomes may not be accurate.

Last but not least, research has revealed barriers in the adoption of telemedicine technologies (Kruse et al., n.d.). Although the value of smartphone-based rehabilitation has been recognized by the research community and the market,

Table 5. Design Recommendations.

Recommendation	Details
1 Consider advanced functionality	Consider additional functions (e.g., progress management and caregiver–patient communication in the development of future mHealth systems as means for improving rehabilitation exercise patient confidence, and therapy adherence.
2 Explore multimodal feedback	Carefully choose the feedback modality that is most suitable for the purpose of any system under development, based on the current literature and/or pilot testing.
3 Apply usability consideration	Apply usability techniques to future mHealth systems design (e.g., for example, task analysis, usability heuristic evaluation and usability testing)
4 Validate system with clinical evidence	Encourage collaboration between technical and clinical teams as a basis for developing and validating future systems with clinical evidence.
5 Increase application variety	Study mHealth systems for a larger variety of chronic diseases as a potential tool for preventing risk factors and reducing disease complications.
6 Explore new technologies	Explore newly available sensor technologies to broaden patient behavior monitoring capabilities and to support therapy for many health conditions.
7 Ensure user safety	Present reliable information and deliver appropriate alerts and advisories in order to ensure medical safety.
8 Protect patient privacy	Apply engineering safety consideration to prevent unanticipated harm or discomfort to users.
9 Improve data quality	Take measures, such as encrypted data transfer and strict access authentication, to guarantee patient safety and privacy before launching a product.
10 Advocate benefits of smartphone-based rehabilitation systems	Design alerts of sensor and data integrity faults in to future mhealth applications to ensure patients are aware of situations in which application outcomes may not be accurate. Convey information on application capabilities and potential benefits to the public and identify opportunities to deliver such systems to a broad population.

it is necessary to convey information on application capabilities and potential benefits to the public and identify opportunities to deliver such systems to a broad population.

Table 5 presents a summary of all the smartphone-based tele-rehabilitation application design recommendations identified on the basis of our literature review. The recommendations are primarily aimed at mHealth application researchers for promoting usable, valid and beneficial future system designs and devices.

Conclusion

Smartphone-based tele-rehabilitation systems have emerged in the last decade and have grown exponentially. Our review was intended to identify the state-of-art of research and development of such systems. Based on search results from the WoS, we classified relevant studies by in terms of target medical conditions. Major condition categories included stroke, balance/stability impairment, cardiac disease and joint/limb rehabilitation. We created a taxonomy of key technologies as well as monitored responses or outcomes of systems. We also determined technological maturity levels based on the documented stages of system development. A few systems were developed as computerized clinical assessment tools for physical therapy and were analyzed separately. The second objective of this study was to formulate design recommendations and identify challenges in the development of smartphone-based rehabilitation systems. The results of this study may be useful for researchers and companies developing future mhealth and tele-rehabilitation systems. Developers may gain insights from more mature systems and the latest research as a basis for designing system functions and selecting appropriate technologies.

One limitation of this study was the exclusion of documents that are not related to physical rehabilitation (e.g., depression). A broader review of smartphone-based health-care systems might reveal additional information on application design approaches and solutions with relevance to patient safety or privacy issues. Second, we did not include studies that only focused on activity recognition technology. Such additional review might shed light on new system design options with

the latest sensor technologies. Finally, we only reviewed accessible articles based on WoS results. The use of multiple scientific literature search engines (e.g., Ei Compendex) might result in more research articles and additional findings.

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Disclosure Statement

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References

- Afzal, M. R., Byun, H.-Y., Oh, M.-K., & Yoon, J. (2015). Effects of kinesthetic haptic feedback on standing stability of young healthy subjects and stroke patients. *Journal of Neuroengineering and Rehabilitation*, 12(1), 27. doi:10.1186/s12984-015-0020-x
- Afzal, M. R., Hussain, I., Jan, Y., & Yoon, J. (2013). Design of a haptic cane for walking stability and rehabilitation. In *13th International Conference on Control, Automation and Systems (ICCAS)* (pp. 1450–1454). IEEE doi:10.1109/ICCAS.2013.6704114

- Afzal, M. R., Oh, M.-K., Choi, H. Y., & Yoon, J. (2016). A novel balance training system using multimodal biofeedback. *Biomedical Engineering Online*, 15. doi:10.1186/s12938-016-0160-7
- Allen, B., Derveloy, R., Lowry, K., Handley, H., Fell, N., Gasior, W., ... Sartipi, M. (2013). Evaluation of fall risk for post-stroke patients using bluetooth low-energy wireless sensor. *Global Communications Conference (GLOBECOM)* (pp. 2598–2603). Atlanta, GA: IEEE
- Banos, O., Moral-Munoz, J. A., Diaz-Reyes, I., Arroyo-Morales, M., Damas, M., Herrera-Viedma, E., ... Villalonga, C. (2015). mDurance: A novel mobile health system to support trunk endurance assessment. *Sensors*, 15(6), 13159–13183. doi:10.3390/s150613159
- Bercht, D., Boisvert, T., Lowe, J., Stearns, K., & Ganz, A. (2012). ARhT: A portable hand therapy system. 345 E 47TH ST, 2012 ANNUAL INTERNATIONAL CONFERENCE OF THE IEEE ENGINEERING IN MEDICINE AND BIOLOGY SOCIETY (EMBC) (264–267). New York, NY: IEEE.
- Bittel, A. J., Elazzazi, A., & Bittel, D. C. (2015). Accuracy and precision of an accelerometer-based smartphone app designed to monitor and record angular movement over time. *Telemedicine and E-Health*, 22(4), 302–309. doi:10.1089/tmj.2015.0063
- Bittel, D. C., Bittel, A. J., Williams, C., & Elazzazi, A. (2017). Improving exercise performance with an accelerometer-based smartphone app: A randomized controlled trial. *American Journal of Physical Medicine & Rehabilitation*, 96(5), 307. doi:10.1097/PHM.0000000000000618
- Bril, T. A., David, V., Scherer, M., Jagos, H., Kafka, P., & Sabo, A. (2016). Development of a wearable live-feedback system to support partial weight-bearing while recovering from lower extremity injuries. In A. J. Jansen (Ed.), *ENGINEERING OF SPORT 11* (Vol. 147, pp. 157–162). Amsterdam, Netherlands: ELSEVIER SCIENCE BV. doi:10.1016/j.proeng.2016.06.206
- Brueckner, H.-P., Theimer, W., & Blume, H. (2014). Real-time low latency movement sonification in stroke rehabilitation based on a mobile platform. 345 E 47TH ST, IEEE INTERNATIONAL CONFERENCE ON CONSUMER ELECTRONICS (ICCE) (266–267). NEW YORK, NY 10017 USA:IEEE.
- Busnatu, S. S., & Sinescu, C. (2015). FI-STAR online personalised cardiac rehabilitation solution. *International Journal of Online Engineering*, 11(1).
- Buttorff, C., Ruder, T., & Bauman, M. (2017). Multiple chronic conditions in the United States. Santa Monica, CA: RAND Corporation.
- Capela, N. A., Lemaire, E. D., & Baddour, N. (2015). Feature selection for wearable smartphone-based human activity recognition with able bodied, elderly, and stroke patients. *Plos One*, 10(4). doi:10.1371/journal.pone.0124414
- Capela, N. A., Lemaire, E. D., & Baddour, N. C. (2014). A smartphone approach for the 2 and 6-minute walk test. In 2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (pp. 958–961). 10.1109/EMBC.2014.6943751
- Casamassima, F., Ferrari, A., Milosevic, B., Ginis, P., Farella, E., & Rocchi, L. (2014). A wearable system for gait training in subjects with Parkinson's disease. *Sensors*, 14(4), 6229–6246. doi:10.3390/s140406229
- Chan, M. H. M., Keung, D. T. F., Lui, S. Y. T., & Cheung, R. T. H. (2016). A validation study of a smartphone application for functional mobility assessment of the elderly. *Hong Kong Physiotherapy Journal*, 35, 1–4. doi:10.1016/j.hkpj.2015.11.001
- Chiu, Y.-L., Tsai, Y.-J., Lin, C.-H., Hou, Y.-R., & Sung, W.-H. (2017). Evaluation of a smartphone-based assessment system in subjects with chronic ankle instability. *Computer Methods and Programs in Biomedicine*, 139, 191–195. doi:10.1016/j.cmpb.2016.11.005
- Choi, Y.-H., Ku, J., Lim, H., Kim, Y. H., & Paik, N.-J. (2016). Mobile game-based virtual reality rehabilitation program for upper limb dysfunction after ischemic stroke. *Restorative Neurology and Neuroscience*, 34(3), 455–463. doi:10.3233/RNN-150626
- Chung, H., Ko, H., Thap, T., Jeong, C., Noh, S.-E., Yoon, K.-H., & Lee, J. (2016). Smartphone-based cardiac rehabilitation program: feasibility study. *Plos One*, 11(8). doi:10.1371/journal.pone.0161268
- Ciou, S.-H., Hwang, Y.-S., Chen, -C.-C., Luh, -J.-J., Chen, S.-C., & Chen, Y.-L. (2017). Football APP based on smart phone with FES in drop foot rehabilitation. *Technology and Health Care*, 25(3), 541–555. doi:10.3233/THC-160730
- Clamann, M., & Kaber, D. B. (2012). The effects of haptic and visual aiding on psychomotor task strategy development during virtual reality-based training. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 56, pp.2570–2574). Los Angeles, CA: SAGE Publications.
- Cruz, J., & Morais, N. (2016). Intrarater agreement of elbow extension range of motion in the upper limb neurodynamic test 1 using a smartphone application. *Archives of Physical Medicine and Rehabilitation*, 97(11), 1880–1886. doi:10.1016/j.apmr.2016.05.001
- de la Torre-Díez, I., López-Coronado, M., Vaca, C., Aguado, J. S., & de Castro, C. (2015). Cost-utility and cost-effectiveness studies of telemedicine, electronic, and mobile health systems in the literature: A systematic review. *Telemedicine And E-Health*, 21(2), 81–85. doi:10.1089/tmj.2014.0053
- Dix, A. (2009). *Human-computer interaction*. Boston, MA: Springer. Retrieved from http://link.springer.com/10.1007/978-0-387-39940-9_192
- Dobkin, B. H. (2017). A rehabilitation-internet-of-things in the home to augment motor skills and exercise training. *Neurorehabilitation and Neural Repair*, 31(3), 217–227. doi:10.1177/1545968316680490
- Dobrican, R. A., & Zampunieris, D. (2016). A Proactive solution, using wearable and mobile applications, for closing the gap between the rehabilitation team and cardiac patients. In 2016 IEEE INTERNATIONAL CONFERENCE ON HEALTHCARE INFORMATICS (ICHI), (pp. 146–155) New York, NY: IEEE. doi:10.1109/ICHI.2016.23.
- Edgar, S. R., Swyka, T., Fulk, G., & Sazonov, E. S. (2010). Wearable shoe-based device for rehabilitation of stroke Patients. In 2010 ANNUAL INTERNATIONAL CONFERENCE OF THE IEEE ENGINEERING IN MEDICINE AND BIOLOGY SOCIETY (EMBC), (pp. 3772–3775) New York NY: IEEE. doi:10.1109/IEMBS.2010.5627577.
- Farjadian, A. B., Sivak, M. L., & Mavroidis, C. (2013). SQUID: Sensorized shirt with smartphone interface for exercise monitoring and home rehabilitation. 2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR) (pp. 1–6). doi:10.1109/ICORR.2013.6650451
- Ferrari, A., Ginis, P., Nieuwboer, A., Greenlaw, R., Muddiman, A., & Chiari, L. (2016). Handling Gait Impairments of Persons with Parkinson's Disease by Means of Real-Time Biofeedback in a Daily Life Environment. *International Conference on Smart Homes and Health Telematics*, (Vol. 9677, pp. 250–261). New York, NY: Springer.
- Ferriero, G., Vercelli, S., Sartorio, F., Muñoz Lasa, S., Ilieva, E., Brigatti, E., ... Foti, C. (2013). Reliability of a smartphone-based goniometer for knee joint goniometry. *International Journal of Rehabilitation Research*, 36(2), 146. doi:10.1097/MRR.0b013e32835b8269
- Fleury, A., Mourcou, Q., Franco, C., Diot, B., Demongeot, J., & Vuillermé, N. (2013). Evaluation of a Smartphone-based audio-bio-feedback system for improving balance in older adults-A pilot study. In *Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE* (pp. 1198–1201). IEEE doi:10.1109/EMBC.2013.6609721
- Frederix, I., Sankaran, S., Coninx, K., & Dendale, P. (2016). MobileHeart, a mobile smartphone-based application that supports and monitors coronary artery disease patients during rehabilitation. In *Engineering in Medicine and Biology Society (EMBC), 38th Annual International Conference of the IEEE* (pp. 513–516). IEEE doi:10.1109/EMBC.2016.7590752
- Gill-Body, K. M., Beninato, M., & Krebs, D. E. (2000). Relationship among balance impairments, functional performance, and disability in people with peripheral vestibular hypofunction. *Physical Therapy*, 80(8), 748–758.
- Ginis, P., Nieuwboer, A., Dorfman, M., Ferrari, A., Gazit, E., Canning, C. G., ... Mirelman, A. (2016). Feasibility and effects of home-based smartphone-delivered automated feedback training for gait in people with Parkinson's disease: A pilot randomized controlled trial. *Parkinsonism & Related Disorders*, 22, 28–34. doi:10.1016/j.parkreidis.2015.11.004
- Glynn, L. G., Hayes, P. S., Casey, M., Glynn, F., Alvarez-Iglesias, A., Newell, J., ... Murphy, A. W. (2013). SMART MOVE - a smartphone-based intervention to promote physical activity in

- primary care: Study protocol for a randomized controlled trial. *Trials*, 14, 157. doi:10.1186/1745-6215-14-157
- Goldman Sachs Report: *How the Internet of Things Can Save the American Healthcare System \$305 Billion Annually*. (2016). June 23). Retrieved January 15, 2018, from <https://www.engagemobile.com/goldman-sachs-report-how-the-internet-of-things-can-save-the-american-healthcare-system-305-billion-annually/>.
- Graettinger, C. P., Garcia, S., Sivi, J., Schenk, R. J., & Syckle, V., . & J., . P. (2002). *Using the Technology Readiness Levels Scale to Support Technology Management in the DOD's ATD/STO Environments* (No. CMU/SEI-2002-SR-027). Pittsburgh, PA: Carnegie Mellon University. Retrieved from <http://www.dtic.mil/docs/citations/ADA407785>
- Guo, J., Smith, T., Messing, D., Tang, Z., Lawson, S., & Feng, J. H. (2015). ARMStrokes: A Mobile App for Everyday Stroke Rehabilitation. In *ASSETS'15: PROCEEDINGS OF THE 17TH INTERNATIONAL ACM SIGACCESS CONFERENCE ON COMPUTERS & ACCESSIBILITY*, (pp. 429-430) New York, NY: ASSOC COMPUTING MACHINERY. doi:10.1145/2700648.2811337.
- Habib, M., Mohktar, M., Kamaruzzaman, S., Lim, K., Pin, T., & Ibrahim, F. (2014). Smartphone-Based Solutions for Fall Detection and Prevention: Challenges and Open Issues. *Sensors*, 14(4), 7181-7208. doi:10.3390/s140407181
- Hackos, J. T., & Redish, J. (1998). *User and task analysis for interface design*. New York, NY: John Wiley & Sons, Inc.
- Halic, T., Kockara, S., Demirel, D., Willey, M., & Eichelberger, K. (2014). MoMiReS: Mobile mixed reality system for physical & occupational therapies for hand and wrist ailments. In *Innovations in Technology Conference (InnoTek)* (pp. 1-6). IEEE. doi:10.1109/InnoTek.2014.6877376
- health.gov. (n.d.). Evidence Portfolio - Chronic Conditions Subcommittee, Question 2. Retrieved February 14, 2019, from https://health.gov/paguidelines/second-edition/report/supplementary-material/pdf/Chronic_Conditions_Q2_Osteoarthritis_Evidence_Portfolio.pdf
- Hodge, D. R., & Lacasse, J. R. (2011). Ranking disciplinary journals with the Google Scholar h-index: A new tool for constructing cases for tenure, promotion, and other professional decisions. *Journal of Social Work Education*, 47(3), 579-596. doi:10.5175/JSWE.2011.201000024
- How, T.-V., Chee, J., Wan, E., & Mihailidis, A. (2013). MyWalk: A Mobile app for gait asymmetry rehabilitation in the Community. In *PROCEEDINGS OF THE 2013 7TH INTERNATIONAL CONFERENCE ON PERSVASIVE COMPUTING TECHNOLOGIES FOR HEALTHCARE AND WORKSHOPS (PERVASIVEHEALTH 2013)*, (pp. 73-76) New York, NY: IEEE. doi:10.4108/icst.pervasivehealth.2013.252118.
- Jansen-Kosterink, S., Vollenbroek-Hutten, M., & Hermens, H. (2016). A renewed framework for the evaluation of telemedicine. *Venice, Italy: 8th International Conference on eHealth, Telemedicine, and Social Medicine: E^{TEH}EMED*, Vol. 2016.
- Jones, D., Skrepnik, N., Toselli, R. M., & Leroy, B. (2016). Incorporating Novel Mobile Health Technologies Into Management of Knee Osteoarthritis in Patients Treated With Intra-Articular Hyaluronic Acid: Rationale and Protocol of a Randomized Controlled Trial. *JMIR Research Protocols*, 5(3), 27-36. doi:10.2196/resprot.5940
- Ketchell, R. I. (2017). Telemedicine is the way forward for the management of cystic fibrosis-The case in favour. *Paediatric Respiratory Reviews*, 26, 19-21.
- Konradsen, L. (2002). Sensori-motor control of the uninjured and injured human ankle. *Journal of Electromyography and Kinesiology*, 12(3), 199-203. doi:10.1016/S1050-6411(02)00021-4
- Koslover, R. L., Gleeson, B. T., De Bever, J. T., & Provancher, W. R. (2012). Mobile navigation using haptic, audio, and visual direction cues with a handheld test platform. *IEEE Transactions on Haptics*, 5(1), 33-38. doi:10.1109/TOH.2011.58
- Kruse, C. S., Karem, P., Shifflett, K., Vegi, L., Ravi, K., & Brooks, M. (n.d.). Evaluating barriers to adopting Telemedicine worldwide. *A Systematic Review*. doi:10.1177/1357633X16674087
- Kumar, S., Nilsen, W., Pavel, M., & Srivastava, M. (2013). Mobile health: Revolutionizing healthcare through transdisciplinary research. *Computer*, 1(1), 28-35. doi:10.1109/MC.2012.392
- Lai, J. C. K., Woo, J., Hui, E., & Chan, W. M. (2004). Telerehabilitation - A new model for community-based stroke rehabilitation. *Journal of Telemedicine and Telecare*, 10(4), 199-205. doi:10.1258/1357633041424340
- Lee, B.-C., & Fung, A. (2015). Smartphone-based sensory augmentation technology for home-based balance training. *2015 15TH INTERNATIONAL CONFERENCE ON CONTROL, AUTOMATION AND SYSTEMS (ICCAS)* (947-952). New York, NY: IEEE.
- Lee, W. W., Yen, S.-C., Tay, A., Zhao, Z., Xu, T. M., Ling, K. K. M., ... Huat, G. K. C. (2014). A Smartphone-Centric System for the Range of Motion Assessment in Stroke Patients. *Ieee Journal of Biomedical and Health Informatics*, 18(6), 1839-1847. doi:10.1109/JBHI.2014.2301449
- LeMoyné, R., Mastroianni, T., Hessel, A., & Nishikawa, K. (2015). Ankle Rehabilitation System with Feedback from a Smartphone Wireless Gyroscope Platform and Machine Learning Classification. In *2015 IEEE 14TH INTERNATIONAL CONFERENCE ON MACHINE LEARNING AND APPLICATIONS (ICMLA)*, (pp. 406-409) Amsterdam, Netherlands: ELSEVIER SCIENCE BV. doi:10.1109/ICMLA.2015.213.
- Lin, F., Wang, A., Zhuang, Y., Tomita, M. R., & Xu, W. (2016). Smart Insole: A Wearable Sensor Device for Unobtrusive Gait Monitoring in Daily Life. *Ieee Transactions on Industrial Informatics*, 12(6), 2281-2291. doi:10.1109/TII.2016.2585643
- Liu, T., Huang, H., Qian, G., Zhao, Y., Jones, M., Zeng, W., ... Fu, J. (2016). A Novel Mobile-Computing Based Assistive Approach for Knee Injury Telerehabilitation-A Preliminary Study. In *International Conference On Human-Computer Interaction*, (Vol. 618, pp. 324-329). Springer.
- Maddison, R., Rawstorn, J. C., Rolleston, A., Whittaker, R., Stewart, R., Benatar, J., ... Gant, N. (2014). The remote exercise monitoring trial for exercise-based cardiac rehabilitation (REMOTE-CR): A randomised controlled trial protocol. *BMC Public Health*, 14. doi:10.1186/1471-2458-14-1236
- Marzano, G., Ochoa-Siguencia, L., & Pellegrino, A. (2017). Towards a New Wave of Telerehabilitation Applications. *Perspective*, 1(1).
- Matera, G., Boonyasirikool, C., Saggini, R., Pozzi, A., & Pegoli, L. (2016). The New Smartphone Application for Wrist Rehabilitation. *Journal Of Hand Surgery-Asian-Pacific Volume*, 21(1), 2-7. doi:10.1142/S2424835516400014
- Mazilu, S., Blanke, U., Dorfman, M., Gazit, E., Mirelman, A., Hausdorff, J. M., & Troester, G. (2015). A wearable assistant for gait training for parkinson's disease with freezing of gait in out-of-the-lab environments. *Acm Transactions on Interactive Intelligent Systems*, 5(1). doi:10.1145/2701431
- Megalingam, R. E. K., Pocklassery, G., Jayakrishnan, V., Mourya, G., & Thulasi, A. A. (2014). Smartphone Based Continuous Monitoring System for Home-bound Elders and Patients. 345 E 47TH ST. In *2014 INTERNATIONAL CONFERENCE ON COMMUNICATIONS AND SIGNAL PROCESSING (ICCSP)*. New York, NY: IEEE.
- Milanese, S., Gordon, S., Buettner, P., Flavell, C., Ruston, S., Coe, D., ... McCormack, S. (2014). Reliability and concurrent validity of knee angle measurement: Smart phone app versus universal goniometer used by experienced and novice clinicians. *Manual Therapy*, 19, 569-574. doi:10.1016/j.math.2014.05.009
- Mitchell, K., Gutierrez, S. B., Sutton, S., Morton, S., & Morgenthaler, A. (2014). Reliability and validity of goniometric iPhone applications for the assessment of active shoulder external rotation. *Physiotherapy Theory and Practice*, 30(7), 521-525. doi:10.3109/09593985.2014.900593
- Molich, R., & Nielsen, J. (1990). Improving a Human-computer Dialogue. *Commun. ACM*, 33(3), 338-348. doi:10.1145/77481.77486
- Mourcou, Q., Fleury, A., Diot, B., & Vuillerme, N. (2016). iProprio: A Smartphone-based system to measure and improve proprioceptive function. In *Engineering in Medicine and Biology Society (EMBC), 2016 IEEE 38th Annual International Conference of the* (pp. 2622-2625). Orlando, FL: IEEE.
- Mourcou, Q., Fleury, A., Franco, C., Diot, B., & Vuillerme, N. (2015). Smartphone-based system for sensorimotor control assessment, monitoring, improving and training at home. In *Inclusive smart cities and e-health* (pp. 141-151). Cham, Switzerland: Springer. doi:10.1007/978-3-319-19312-0_12

- National Institute on Disability, Independent Living, and Rehabilitation Research. (2017). NIDILRR Frameworks | ACL Administration for Community Living. Retrieved from <https://acl.gov/aging-and-disability-in-america/nidilrr-frameworks>
- Nishiguchi, S., Ito, H., Yamada, M., Yoshitomi, H., Furu, M., Ito, T., ... Tsuboyama, T. (2016). Self-assessment of Rheumatoid Arthritis Disease Activity Using a Smartphone Application Development and 3-month Feasibility Study. *Methods of Information in Medicine*, 55(1), 65–69. doi:10.3414/ME14-01-0106
- O'Brien, H. L., & Toms, E. G. (2010). The development and evaluation of a survey to measure user engagement. *Journal of the American Society for Information Science and Technology*, 61(1), 50–69. doi:10.1002/asi.21229
- Ongvisatepaiboon, K., Chan, J. H., & Vanijja, V. (2015a). Smartphone-Based Tele-Rehabilitation System for Frozen Shoulder Using a Machine Learning Approach. *2015 IEEE Symposium Series on Computational Intelligence* (pp. 811–815). doi:10.1109/SSCI.2015.120
- Ongvisatepaiboon, K., Vanijja, V., & Chan, J. H. (2015b). Smartphone-based tele-rehabilitation framework for patient with frozen shoulder. *Frontiers in Artificial Intelligence and Applications*, 275, 158–169. doi:10.3233/978-1-61499-503-6-158
- Ongvisatepaiboon, K., Vanijja, V., Chignell, M., Mekhora, K., & Chan, J. H. (2016). Smartphone-Based Audio-Biofeedback System for Shoulder Joint Tele-Rehabilitation. *Journal of Medical Imaging and Health Informatics*, 6(4), 1127–1134. doi:10.1166/jmihi.2016.1810
- Pantelopoulou, A., & Bourbakis, N. G. (2010). A survey on wearable sensor-based systems for health monitoring and prognosis. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 40(1), 1–12. doi:10.1109/TSMCC.2009.2032660
- Patel, M. D., Tilling, K., Lawrence, E., Rudd, A. G., Wolfe, C. D. A., & McKeivitt, C. (2006). Relationships between long-term stroke disability, handicap and health-related quality of life. *Age and Ageing*, 35(3), 273–279. doi:10.1093/ageing/afj074
- Pepa, L., Capecci, M., Verdini, F., Ceravolo, M. G., & Spalazzi, L. (2015). An Architecture to Manage Motor Disorders in Parkinson's Disease. In *2015 IEEE 2ND WORLD FORUM ON INTERNET OF THINGS (WF-IOT)* (pp. 615–620). New York, NY: IEEE.
- Pereira, M., Almeida, A. M., & Caixinha, H. (2016). Exercit@ rt mobile: Monitoring of pulmonary rehabilitation in COPD. In *Technology and Innovation in Sports, Health and Wellbeing (TISHW), International Conference on* (pp. 1–8). Vila Real, Portugal: IEEE.
- Peretti, A., Amenta, F., Tayebati, S. K., Nittari, G., & Mahdi, S. S. (2017). Telerehabilitation: Review of the State-of-the-Art and Areas of Application. *JMIR Rehabilitation and Assistive Technologies*, 4(2), e7. doi:10.2196/rehab.7511
- Perez, A. A., & Labrador, M. A. (2016). A Smartphone-based System for Clinical Gait Assessment. In *2016 IEEE INTERNATIONAL CONFERENCE ON SMART COMPUTING (SMARTCOMP)* (pp. 39–46). New York, NY: IEEE.
- Pew Research Center. (2019, February 5). Smartphone Ownership Is Growing Rapidly Around the World, but Not Always Equally | Pew Research Center. February 13, 2019, Retrieved from <http://www.pewglobal.org/2019/02/05/smartphone-ownership-is-growing-rapidly-around-the-world-but-not-always-equally/>
- Pourahmadi, M. R., Ebrahimi Takamjani, I., Sarrafzadeh, J., Bahramian, M., Mohseni-Bandpei, M. A., Rajabzadeh, F., & Taghipour, M. (2017). Reliability and concurrent validity of a new iPhone goniometric application for measuring active wrist range of motion: A cross-sectional study in asymptomatic subjects. *Journal of Anatomy*, 230(3), 484–495. doi:10.1111/joa.12568
- Pu, F., Fan, X., Yang, Y., Chen, W., Li, S., Li, D., & Fan, Y. (2014). Feedback System Based on Plantar Pressure for Monitoring Toe-Walking Strides in Children with Cerebral Palsy. *American Journal of Physical Medicine & Rehabilitation*, 93(2), 122–129. doi:10.1097/PHM.0b013e3182a54207
- QYResearch Group. (2017). *Global Virtual Rehabilitation Systems Market Research Report 2017* (ID. 2113).
- Rauterberg, M. (1998). About the importance of auditory alarms during the operation of a plant simulator. *Interacting with Computers*, 10(1), 31–44. doi:10.1016/S0953-5438(97)00038-6
- Rawstorn, J. C., Gant, N., Meads, A., Warren, I., & Maddison, R. (2016). Remotely Delivered Exercise-Based Cardiac Rehabilitation: Design and Content Development of a Novel mHealth Platform. *Jmir Mhealth and Uhealth*, 4(2), 430–445. doi:10.2196/mhealth.5501
- Redd, C. B., & Bamberg, S. J. M. (2012). A Wireless Sensory Feedback Device for Real-Time Gait Feedback and Training. *Ieee-Asme Transactions On Mechatronics*, 17(3), 425–433. doi:10.1109/TMECH.2012.2189014
- Riemann, B. L., & Guskiewicz, K. M. (2000). Effects of Mild Head Injury on Postural Stability as Measured Through Clinical Balance Testing. *Journal of Athletic Training*, 35(1), 19–25.
- Rowlands, D. D., Usher, W., McCarthy, M., Leadbetter, R., Ride, J., Casey, L., ... James, D. A. (2013). An Automated Activity Monitoring System for Rehabilitation. *Procedia Engineering*, 60(Supplement C), 232–237. doi:10.1016/j.proeng.2013.07.034
- Seipel, M. M. O. (2003). Assessing publication for tenure. *Journal of Social Work Education*, 39(1), 79–88. doi:10.1080/10437797.2003.10779120
- Şenel, E., & Demir, E. (2015). A global productivity and bibliometric analysis of telemedicine and teledermatology publication trends during 1980–2013. *Dermatologica Sinica*, 33(1), 16–20. doi:10.1016/j.dsi.2014.10.003
- Shadgan, B., Roig, M., Hajghanbari, B., & Reid, W. D. (2010). Top-cited articles in rehabilitation. *Archives of Physical Medicine and Rehabilitation*, 91(5), 806–815. doi:10.1016/j.apmr.2010.01.011
- Shin, D. C., & Song, C. H. (2016). Smartphone-Based Visual Feedback Trunk Control Training Using a Gyroscope and Mirroring Technology for Stroke Patients: Single-blinded, Randomized Clinical Trial of Efficacy and Feasibility. *American Journal of Physical Medicine & Rehabilitation*, 95(5), 319–329. doi:10.1097/PHM.0000000000000447
- Singh, A., Piana, S., Pollarolo, D., Volpe, G., Varni, G., Tajadura-Jiménez, A., ... Bianchi-Berthouze, N. (2016). Go-with-the-flow: Tracking, analysis and sonification of movement and breathing to build confidence in activity despite chronic pain. *Human-Computer Interaction*, 31(3–4), 335–383. doi:10.1080/07370024.2015.1085310
- Snoek, J. A., Meindersma, E. P., & Prins, L. F., van't Hof, A. W., Hopman, M. T., de Boer, M.-J., & de Kluiver, E. P. (2016). Rationale and design of a randomised clinical trial for an extended cardiac rehabilitation programme using telemonitoring: The TeleCaRe study. *BMC Cardiovascular Disorders*, 16(1), 175.
- Stafford, M., Lin, F., & Xu, W. (2016). Flappy Breath: A Smartphone-Based Breath Exergame. In *2016 IEEE FIRST INTERNATIONAL CONFERENCE ON CONNECTED HEALTH: APPLICATIONS, SYSTEMS AND ENGINEERING TECHNOLOGIES (CHASE)*, (pp. 332–333) New York, NY: IEEE. doi:10.1109/CHASE.2016.70.
- Tyson, S. F., Hanley, M., Chillala, J., Selley, A., & Tallis, R. C. (2006). Balance Disability After Stroke. *Physical Therapy*, 86(1), 30–38. doi:10.1093/ptj/86.1.30
- Uscher-Pines, L., Mulcahy, A., Cowling, D., Hunter, G., Burns, R., & Mehrotra, A. (2016). Access and Quality of Care in Direct-to-Consumer Telemedicine. *Telemedicine And E-Health*, 22(4), 282–287. doi:10.1089/tmj.2015.0079
- Valentiner, L. S., Ried-Larsen, M., Karstoft, K., Brinklov, C. F., Brons, C., Nielsen, R. O., ... Langberg, H. (2017). Long-term effect of smartphone-delivered Interval Walking Training on physical activity in patients with type 2 diabetes: Protocol for a parallel group single-blinded randomised controlled trial. *BMJ Open*, 7(4). doi:10.1136/bmjopen-2016-014036
- Vorrink, S. N. W., Kort, H. S. M., Troosters, T., Zanen, P., & Lammers, J.-W. J. (2016). Efficacy of an mHealth intervention to stimulate physical activity in COPD patients after pulmonary rehabilitation. *European Respiratory Journal*, 48(4), 1019–1029. doi:10.1183/13993003.00083-2016
- Wagner, R., & Ganz, A. (2012). PAGAS: Portable and Accurate Gait Analysis System. 345 E 47TH ST, 2012 ANNUAL INTERNATIONAL CONFERENCE OF THE IEEE ENGINEERING IN MEDICINE AND BIOLOGY SOCIETY (EMBC) (280–283). New York, NY: IEEE.
- Wai, A. A. P., Duc, P. D., Syin, C., & Haihong, Z. (2014). iBEST: Intelligent balance assessment and stability training system using smartphone. In *Engineering in Medicine and Biology Society*

- (EMBC), 2014 36th Annual International Conference of the IEEE (pp. 3683–3686). New York, NY: IEEE.
- Wang, H.-P., Guo, A.-W., Bi, Z.-Y., Zhou, Y.-X., Wang, Z.-G., & Lu, X.-Y. (2016). A Novel Distributed Functional Electrical Stimulation and Assessment System for Hand Movements Using Wearable Technology. 345 E 47TH ST, *PROCEEDINGS OF 2016 IEEE BIOMEDICAL CIRCUITS AND SYSTEMS CONFERENCE (BIOCAS)* (74–77). New York, NY: IEEE.
- Wang, Q. (2016). Designing Posture Monitoring Garments to Support Rehabilitation. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (pp. 709–712). New York, NY: ACM. doi:10.1145/2839462.2854106
- Wang, Q., Chen, W., & Markopoulos, P. (2014). Smart garment design for rehabilitation. In *International Workshop on ICTs for Improving Patients Rehabilitation Research Techniques* (pp. 260–269). Springer.
- Worringham, C., Rojek, A., & Stewart, I. (2011). Development and feasibility of a smartphone, ECG and GPS based system for remotely monitoring exercise in cardiac rehabilitation. *PloS One*, 6(2), e14669. doi:10.1371/journal.pone.0014669
- Wu, Y., Yao, X., Vespasiani, G., Nicolucci, A., Dong, Y., Kwong, J., ... Li, S. (2017). Mobile App-Based Interventions to Support Diabetes Self-Management: A Systematic Review of Randomized Controlled Trials to Identify Functions Associated with Glycemic Efficacy. *Jmir MHealth And UHealth*, 5(3), e35. doi:10.2196/mhealth.6522
- Yang, Y.-T., Iqbal, U., Ching, J. H.-Y., Ting, J. B.-S., Chiu, H.-T., Tamashiro, H., & Hsu, Y.-H. E. (2015). Trends in the growth of literature of telemedicine: A bibliometric analysis. *Computer Methods and Programs in Biomedicine*, 122(3), 471–479. doi:10.1016/j.cmpb.2015.09.008
- Yudi, M. B., Clark, D. J., Tsang, D., Jelinek, M., Kalten, K., Joshi, S., ... Farouque, O. (2016). SMARTphone-based, early cardiac REHAbilitation in patients with acute coronary syndromes [{} SMART-REHAB Trial]: A randomized controlled trial protocol. *BMC Cardiovascular Disorders*, 16. doi:10.1186/s12872-016-0356-6