Wearable technologies for active living and rehabilitation: Current research challenges and future opportunities

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Abstract
This paper presents some recent developments in the field of wearable sensors and systems that are relevant to rehabilitation and provides examples of systems with evidence supporting their effectiveness for rehabilitation. A discussion of current challenges and future developments for selected systems is followed by suggestions for future directions needed to advance towards wider deployment of wearable sensors and systems for rehabilitation.

Keywords
Wearable technology, smart systems (rehabilitation), wearable sensor systems, virtual reality, augmented reality, rehabilitation, interactive feedback, functional electrical stimulation

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Introduction
Rapidly changing demographics in the United States and advancements in critical care treatments have led to an increasing need for solutions that promote wellness management and rehabilitation outside of the clinical environment. To be successful, any wellness or rehabilitation interventions need to be multifaceted, from addressing biological function at the cellular level to community support at the personal level. Providing effective rehabilitation is an increasingly complex challenge because of the increased number of individuals with multiple medical conditions and disabilities and the subsequent reduction of access to providers.1 Recent advances in technology, including wearable sensor systems, may significantly enhance the effectiveness of rehabilitation interventions and help to address health disparities.3

Disablement models are helpful for framing how emerging technologies need to fit in a multifaceted solution to be effective in rehabilitation interventions. Several different models define disability and related concepts, including the Disablement Model developed by Nagi,4 the International Classification of Impairments, Disabilities and Handicaps,5 and its current revision, International Classification of Functioning, Disability and Health.6 However, they all view overall disablement as a series of related concepts describing the consequences or impact of a health condition on a person’s body, their activities, and on their societal participation.7

Understanding the context of an individual’s disablement is key to optimizing the use of recent advances in technology, including wearable sensor systems, for diagnostic, monitoring and treatment applications.

In this paper, we define wearable technology as “devices that can be worn or mated with human skin to continuously and closely monitor an individual’s activities, without interrupting or limiting the user’s motions”.8 Wearable technology most commonly refers to electronic technologies, but it can also include products such as smart or advanced materials used in clothing or protective equipment. There are three

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general use-cases for wearable devices: (1) prediction of future events, (2) detection of anomalous, critical events, and (3) diagnostic monitoring to improve decision-making. This review focuses primarily on technologies and examples for physical rehabilitation, though this is often only part of an integrated rehabilitation approach that may include cognitive and psychosocial rehabilitation.

There have been tremendous advances in the field of wearable sensors for health monitoring, though theories and evidence for using these sensors widely in rehabilitation and how to best improve outcomes through behavior change are lagging. Other challenges include societal issues such as expectations for privacy and data security, technological issues such as battery lifetime, and cultural barriers such as the consumer’s perception of a stigma associated with using medical devices for home-based clinical monitoring. This review aims to summarize some recent developments in the field of wearable sensors and systems relevant to the field of rehabilitation and provide examples of systems with evidence supporting their effectiveness. Current challenges and opportunities for moving these technologies forward for wider-use outside clinical research settings are discussed, highlighting the technologies and evidence needed, and potential future developments that may alter current paradigms.

**Current developments in wearable technologies for rehabilitation**

In this section, we present some illustrative examples of techniques and applications of wearable technologies and systems for rehabilitation. Virtual reality (VR) systems, functional electrical stimulation (FES), and activity trackers are some of the current wearable technologies being applied to rehabilitation. However, it is important to realize that these advances are in the context of systems. As discussed by Wang et al., interactive wearable systems facilitating rehabilitation exercise programs are often developed for specific health applications such as patients with neurological conditions, musculoskeletal conditions, chronic pulmonary impairment, or with pain. Most systems are used for monitoring and providing rapid user feedback on posture and extremity movements, and are not networked, smart, or designed for continuous use. Designing these devices as non-obtrusive and intuitive systems for longer-term home-use and connecting these devices to internet services may dramatically widen their range of applications.

**Advanced wearable sensors**

To date, accelerometers and inertial measurement units are the most frequently used sensors in wearable systems, and provide measurements that can be used to track range of motion and performance. A large number of studies using these sensors have focused on upper body rehabilitation following stroke, and there is some clinical evidence of small improvements, however few randomized clinical trials have been carried out. Increasingly, these systems are interactive and provide more than basic feedback and require less setup and monitoring time by healthcare professionals. Under development are a wider range of wearable sensor systems that may assist in home-based rehabilitation, including body sensor networks, smart clothing, and wearable cameras that provide complementary information to these movement sensors.

Body-worn sensors now come in many shapes and sizes, including chest-worn heart-monitoring straps, headbands for brain-activity measuring electroencephalograms (EEGs), posture-detecting monitors, baby and pregnancy monitors for measuring vitals and movement, and electronic patches. These sensors can provide insights into heart rate, respiratory rate, oxygen saturation and blood pressure, and can detect vital sign abnormalities that provide important contextual information or provide feedback to the wearers. In a study of 16 cardiac rehabilitation patients, a suite of sensors tracking body movement was compared against vital sign measures to track energy expenditure during low-to-moderate intensity daily activities to develop a predictive model for efficacy of beta-blockers. The availability of consumer-grade devices with vital sensors, such as smart watches and chest straps has significantly reduced the barrier to incorporation of these sensors in studies. However, challenges exist with the calibration, accuracy, and sensitivity of these devices for medical applications.

Smart clothing can be considered the ultimate wearable system, as it can integrate into everyday life as part of a garment and/or footwear, and track or measure physiological, contextual or biometric attributes. For example, the Neofect’s RAPAI Smart Glove allows people to rehabilitate their hands by wearing a glove and using accompanying technology. This can be used to recover from injuries, or to help with issues that could arise from adrenoleukodystrophy or other neurological disorders. In a randomized clinical trial using a four-week training program with the Smart Glove, both Fugl–Meyer score and Jebsen–Taylor test scores were improved and retained one month after training completion.

Wearable cameras have been developed for training clinicians and for remote rehabilitation consultation. Chen et al. incorporated wearable cameras and motion sensors in a rehabilitation exercise assessment for knee osteoarthritis that enables the patient to self-manage rehabilitation progress. Accuracy for exercise...
type classification was 97% and for exercise posture identification was 88%, demonstrating feasibility of the system for rehabilitation assessment. Emerging technologies like 360° vision, VR, artificial intelligence, deep learning, and computer vision will enhance the wearable camera experience, expanding the devices’ use cases and applications.

Wearable sensor systems provide the opportunity to not only evaluate rehabilitation as it occurs during daily life activities but also to provide timely, meaningful feedback to patients and their therapists. Such feedback can guide and motivate progressive skills practice aimed at maximizing the recovery of motor function. However, a number of challenges exist related to the accuracy and reproducibility of these sensors, design optimization, system integration, consideration of user experience, the need for user education, and securing reimbursement. Underlying these challenges is the need for stronger evidence on the longer-term effectiveness of these sensor technologies for rehabilitation in both clinical and home settings.

Virtual and augmented reality systems

Augmented reality (AR) headsets like Google Glass and mixed reality systems such as the HoloLens, have been deployed in several industrial and enterprise settings, and there is growing interest in their use for healthcare applications. These systems have become increasingly complex, moving from overlaying digital information towards positional tracking and depth sensors to provide a more immersive experience, and enabling interactions with holographic objects. Increasing numbers of studies have shown positive rehabilitation outcomes using the combination of sensing technology and interactive gaming or VR environments. Munroe et al. designed an AR game to provide home-based neurorehabilitation for children with cerebral palsy. The system combines electromyography electrodes and accelerometers in an armband to provide data. A trained classifier determines whether the target neuromotor performance of the arm is achieved and the user moves a virtual object through therapist-prescribed motions. In addition, VR can help patients undergoing physical rehabilitation as they imagine themselves performing slow, simple movements while immersed. VR immersion, coupled with the patient’s own visualization, is believed to create brain patterns closer to actual motor skills than visualization alone. This gives the patient a huge advantage in healing. In a blinded randomized controlled trial studying 59 stroke survivors, McEwen et al. found that VR exercise intervention for inpatient stroke rehabilitation improved mobility-related outcomes.

There is significant potential for AR and VR systems to enhance rehabilitation programs and to provide real-time feedback to the patient and to their therapist. However, there is limited evidence so far for the long-term efficacy of these systems and whether they offer sustained improvement over traditional approaches. On the other hand, a recent review by Massetti et al. would suggest that VR interventions yielded improvement in motor functions, greater community participation, and improved psychological and cognitive function. As the technology of AR/VR systems continues to improve, additional clinical studies are needed to generate the evidence base demonstrating the utility and efficacy of such systems for clinical care and research in rehabilitation.

Functional electrical stimulation

Traditionally, functional electrical stimulation (FES) or neuromuscular electrical stimulators have been utilized predominantly for stimulating lower and upper extremity functions. For many years, FES systems included a battery-powered stimulator connected with lead wires to the stimulating electrodes and a wired external trigger to synchronize muscle contraction with the functional activity. More recently, academic researchers and commercial companies are developing wearable, wireless FES systems. These systems are self-administered and controlled by the patient. Having low profile, they can be worn comfortably under clothing while functioning in the home and the community.

Current research approaches to improve recovery of connectivity of the brain’s motor network include application of iterative algorithms and closed-loop control of the desired level of the electrically induced contraction of the target muscles. Appropriate closed-loop control design should enable each patient to use their internal sensory-motor control system and add FES only to complete whatever motion the internal control failed to achieve, while walking or using the paretic upper extremity. Examples of research efforts to achieve a reliable, cost-effective, and durable closed-loop control can be found mostly in engineering publications and are still considered “proof of concept” or initial efficacy investigations. Attempts to improve the resolution of FES-induced muscle contraction by using multiplexers and arrays of small electrodes or manipulation of pulse parameters have yielded some interesting discoveries and electronic innovations. However, these research efforts have failed so far to yield a viable commercial product in rehabilitation medicine.

Using telemedicine and cloud data storage, researchers have successfully demonstrated continuous storage of patients’ performance using FES combined with a
motorized cycling system, accumulation of training
doses, and provision of uninterrupted communication
with clinicians.\textsuperscript{45} However, so far, most FES systems
are configured with very limited storage of performance
and compliance. The need to implement FES throughout
the continuum of care, from critical-care units to
home use, presents another key challenge for both
researchers and clinicians. Increasing home-based use
will need new algorithms capable of identifying and
storing essential data of performance, such as clinical
evidence of functional recovery, plateau, or regression,
compliance data, and online communication with clin-
icians. However, with the rapid development of similar
wearable systems, such FES systems are likely to be
available soon.

\textbf{Current challenges and opportunities}

A generally accepted assumption has been that more
data, and in particular data about daily life, will
improve the accuracy and reproducibility of healthcare
models, and enable more efficient remote monitoring.
It is presumed that this will, in turn, improve our ability
to delivery cost-efficient and effective care. However, in
practice, actionable information from wearable devices
is plagued by a number of issues. These include
concerns related to quality, battery lifetime, lack of
contextual information, privacy and security concerns,
as well as variable and proprietary algorithms for annot-
ating data streams. Additionally, many systems are
developed for the fitness market, rather than older
adults and rehabilitation.

The mix of research prototype devices, consumer-
grade, and clinical-grade wearable systems introduces
many challenges in determining efficacy. As a result,
there are concerns about validation, standardization,
and interoperability. When mixed with usability opti-
imized for early-adopters of technology, these concerns
provide a significant barrier for widespread adoption
and utilization of wearables for active living manage-
ment and as a routine part of rehabilitation.

This mix also introduces additional barriers such as
rapid technology obsolescence, use of proprietary data
processing algorithms and formats, and the ability to
scale technologies for larger cohorts and longer studies.
All these challenges slow progress towards generating a
rich evidence base for the effectiveness of these technol-
ogies for rehabilitation. Below we discuss three of these
challenges, followed by a brief description of three
potential areas of opportunity.

\textbf{Power consumption}

While wearable sensor systems can lead to ubiquitous
and personalized rehabilitation service for users, the
need for size reduction to ensure portability can
impose severe restrictions on battery capacity. Energy
harvesting or scavenging has been considered as one
approach to ensure that the useful features of a wear-
able sensor are not outweighed by the battery cost, size,
and weight. However, energy harvesting generally
suffers from low power output, making it a non-ideal
proposition to address the power requirement of the
wearable sensor components such as the accelerometer.
It has been shown that the power requirement of the
accelerometer ranges between 0.35 and 5 times the har-
vested kinetic power for detecting common human
activities with high accuracy.\textsuperscript{46}

Khalifa et al.\textsuperscript{47} have shown that it may be possible to
infer human activities directly from the energy-harvest-
ing pattern, which would eliminate the need to use an
accelerometer. Their system uses kinetic energy harvest-
ing and leverages the fact that different human activities
produce different amount of kinetic energy that can be
leveraged for activity recognition. Initial tests have
shown that even though the new system ("HARKE
or HAR Kinetic Energy") consumes 72\% less energy
than the conventional accelerometer-based system, it
can classify human activities as accurately as the accel-
erometer-based human activity recognition (HAR).
Advances in energy-harvesting hardware have created
an opportunity for realizing battery-free wearables for
continuous and pervasive HAR, though these advances
have yet to be realized in widely available wearable
systems.

\textbf{Measurement and validation}

The calibration and validation of wearable technologies
is critical to obtaining accurate data from them.\textsuperscript{48}
However, the field is still developing a common lan-
guage for measurement and evaluation of devices to
define performance, safety, and durability; this has con-
tributed to the challenges of rigorous calibration and
validation. For example, to establish the performance
of different devices in step counting, a well-defined and
reproducible system that replicates human walking is
needed. Additionally, access to the raw and processed
data is required to help determine whether variations
are due to hardware differences, such as accelerometers,
or due to the post-processing algorithms. However,
these necessarily narrow approaches to calibration do
not capture the complexity of daily life and the vari-
ation in gait and mobility. In general, there is reason-
able intra-class correlation for wearable devices,\textsuperscript{49}
though there are limitations that have been highlighted
in a number of recent studies. For example, one study
noted that readings did not correlate with intensity of
exercise,\textsuperscript{50} and another noted that recorded steps for
some wearables fell to zero for speeds of 0.3–0.5 m/s.\textsuperscript{51}
Ethical and privacy issues

A large range of technology companies and start-up ventures have sprung up to exploit data from sensors such as accelerometers, gyroscopes, and pedometers, breath sensing, heart-rate monitors, and calorie trackers for the potential commercial value. However, this raises the delicate question of data ownership and ethical aspects of data usage and interpretation. Another aspect related to privacy is data leakage about non-health-related issues. Spagnolli et al.52 administered a questionnaire including key dimensions of the Technology Acceptance Model53,54 to 110 respondents (33 women). This questionnaire referenced three devices (smart shirt, portable EEG system, and eye-tracking glasses) and six usage scenarios (dangerous work, heavy work, sport, home care, research, and retail). The study was able to identify several variables as good predictors of device acceptance, such as perceived usefulness, perceived comfort/pleasantness, facilitating conditions, and attitude towards technology. The study also found that while respondents would share information about their stress level, mental states, and cognitive performance with physician, psychologist, and partner, they were more comfortable sharing their interests and preferences with friends and partner. Additionally, non-experts seemed more concerned about privacy than experts. Li et al.55 have shown that in the privacy context, people make decisions about adopting healthcare wearable devices based on perceived risk–benefit ratios. Their study of 333 actual users of healthcare wearable devices showed that people use different lenses to evaluate perceived benefits and perceived risks. Thus, while the perceived benefits were determined by perceived informativeness and functional congruence, the perceived privacy risks were informed by health information sensitivity, personal innovativeness, legislative protection, and perceived prestige.

Human-centered design

An area of opportunity is human-centered design. Designing and developing persuasive, seamless technologies that engage users and reinforce positive behavior on a daily basis is very challenging because of the diverse range of user capabilities, motivations, and desired outcomes.56,57 There is growing interest and published examples of acceptance and usability studies. For example, there are studies of Parkinson’s patients,58 fall detection, and prediction in the homesetting;59 vibration feedback of gait when using lower limb prosthetics,60 and feedback on knee habilitation exercises.61 There is a need for stronger human-centered design approaches, developing interactive systems by focusing on user needs and requirements and applying best practices in usability and ergonomics. If implemented properly, this has the potential to significantly improve satisfaction and sustained use of wearable technologies beyond initial short, incentivized studies.

Personalized models

Human-centered design is focused on developing systems that take into account important factors for definable groups of users. In contrast, personalized models consider the many nuances of the behaviors, needs, and constraints of individual human beings. Personalized systems and models can potentially yield higher rates of adoption of wearable systems, but there are many variables that need to be considered. The rapid rise of a smart and connected health environment including wearable devices, electronic health records, and an integrated care environment has laid the groundwork for having personalized prognostic and predictive models of health to inform wellness and treatment planning. However, development of accurate, personalized forecasting models has been significantly hindered by the degree of inter-individual variability, privacy and security concerns, and inability to efficiently scale these models to a community or national level. Currently, the focus of most personalized models is on understanding and promoting positive health behaviors while retaining patient engagement. The intersection between these behavior changes models and persuasive technology design strategies is particularly of interest for wearable devices.62 Personalized models may also assist with other aspects of wearable technologies, including a better understanding of intention,63 and how to implement and scale-up the computational framework.64

Collocated interactions

As wearable devices proliferate among groups of individuals, as well as per individual, there has been a growing need to understand interactions, both from a social perspective and from the commercial utilization perspective. Research activities have focused over the last decade on studying scenarios ranging from individual to multiuser experiences and interactions.65–68 According to Lucero et al.69 while early research in collocated interactions was centered on device development, the current research has focused more on the experience. They point to multi-player pervasive games such as Blast theory’s “Can You See Me Now?”70 where there is interaction between players in the virtual world and runners in the real world. There is high interactivity with mobile devices, and the gaming
Conclusions

The evidence base for the efficacy of wearables is expanding. However, this evidence is skewed towards short-term physical rehabilitation training, neurological disorders, and rehabilitation after extremity injuries and focused on secondary endpoints rather than long-term outcomes. This evidence is also skewed towards rehabilitation in a care setting and involving a rehabilitation specialist. There is a need to expand this evidence base by carrying out more efficacy studies to support the longer-term use of wearable sensors in a home-setting using self-guided approaches.

To advance our understanding of the use of these systems in rehabilitation, further research and development is needed to address issues of power consumption, standardization, interoperability, measurement validity, privacy, and confidentiality. There are many prototype research systems tackling these issues, and there is wide availability of clinical-grade, and consumer-grade, wearables. However, the reliability and validity of research and consumer-grade systems needs to be more firmly established to support the conclusions drawn from studies using these devices.

For wider-spread adoption of wearables for rehabilitation, understanding of end-use must go hand-in-hand with technology development. Routine and longer-term use of wearables introduces many challenges that are not addressed in short clinical studies, such as durability, power consumption, comfort and usability. Therefore, to advance the use of wearable systems for rehabilitation outside of the clinical setting, a systematic and integrated approach is needed to develop user-centric systems for a wide range of rehabilitation applications. Such an approach will motivate and maintain engagement within the user community, and demonstrate clear long-term health benefits.

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MMR, VMP, and RSC conceived the review. All authors reviewed the literature, wrote the first draft.
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