JMIR Rehabilitation and Assistive Technologies

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Original Paper

Machine Learning to Improve Energy Expenditure Estimation in Children With Disabilities: A Pilot Study in Duchenne Muscular Dystrophy

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Abstract

Background: Children with physical impairments are at a greater risk for obesity and decreased physical activity. A better understanding of physical activity pattern and energy expenditure (EE) would lead to a more targeted approach to intervention.

Objective: This study focuses on studying the use of machine-learning algorithms for EE estimation in children with disabilities. A pilot study was conducted on children with Duchenne muscular dystrophy (DMD) to identify important factors for determining EE and develop a novel algorithm to accurately estimate EE from wearable sensor-collected data.

Methods: There were 7 boys with DMD, 6 healthy control boys, and 22 control adults recruited. Data were collected using smartphone accelerometer and chest-worn heart rate sensors. The gold standard EE values were obtained from the COSMED K4b2 portable cardiopulmonary metabolic unit worn by boys (aged 6-10 years) with DMD and controls. Data from this sensor setup were collected simultaneously during a series of concurrent activities. Linear regression and nonlinear machine-learning–based approaches were used to analyze the relationship between accelerometer and heart rate readings and COSMED values.

Results: Existing calorimetry equations using linear regression and nonlinear machine-learning–based models, developed for healthy adults and young children, give low correlation to actual EE values in children with disabilities (14%-40%). The proposed model for boys with DMD uses ensemble machine learning techniques and gives a 91% correlation with actual measured EE values (root mean square error of 0.017).

Conclusions: Our results confirm that the methods developed to determine EE using accelerometer and heart rate sensor values in normal adults are not appropriate for children with disabilities and should not be used. A much more accurate model is obtained using machine-learning–based nonlinear regression specifically developed for this target population.

Introduction

Accelerometry-based algorithms quantifying the energy estimation (EE) or calories-out of users and measuring physical activity of healthy populations are becoming popular in the consumer electronics market [1,2,3]. Smartphone apps and devices such as Fitbit, Jawbone Up, Nike+ Fuelband, Microsoft Band, and Apple Watch use underlying accelerometer sensors and machine-learning algorithms developed on a pool of healthy adults to give real-time EE estimates. Many of these algorithms rely on fusing heart rate measurements with accelerometer readings. It is tempting to use similar algorithms to quantify the EE of children with disabilities. However, to the best of our

knowledge, there has been limited effort to validate application of machine-learning–based EE algorithms for pediatric patients with muscular dystrophy. A better understanding of real-world community-level physical activity patterns and EE would lead to more targeted interventions to combat obesity and decreased physical activity in this population.

Different measuring techniques have been used in disabled populations including questionnaires, activity diaries, heart rate monitoring, motion sensors (eg, pedometers, accelerometers), indirect calorimetry, and doubly labeled water. Activity questionnaires and diaries, while inexpensive, are time consuming, rely on recall and reporting by the individual, and have been shown to be inaccurate, especially in children [4,5]. Indirect and direct calorimetry cannot be used in home and outdoor scenarios and are restricted to clinical settings. In healthy normal populations, heart rate monitoring has been shown to be less accurate in estimating EE for low-intensity activities, which comprise the majority of the activity for disabled populations [4,5]. Accelerometers are more accurate for nondisabled populations because they measure activities across several planes allowing measurements of the duration, frequency, and intensity of physical activity. Disadvantages include the inability to measure activities where the patient is not moving the part of the body being monitored by the accelerometer (eg, cycling, sitting, standing) [6]. Development of EE algorithms utilizing inertial sensor (accelerometer) data has thus far been largely restricted to healthy adult populations. Sensor-based EE estimation relies on previously developed general formulas, and no data exists for specific pediatric populations including children with disabilities. Simply extending basic EE estimation algorithms developed for healthy adults for use with children with physical disabilities is problematic.

In this study, we will identify important factors for EE calculation and develop algorithms that accurately estimate EE for a specific target pediatric population, children with Duchenne muscular dystrophy (DMD). These data can then be used to measure community habitual physical activity and EE using sensors.

DMD is one of the most common hereditary (X-linked recessive) neuromuscular disorders affecting the pediatric population and also represents a prototypical muscle disorder with proximal limb girdle weakness that results in a wide spectrum of physical impairments. Its prevalence is approximately 1 per 3500 to 5000 boys, making it the most common and severe form of childhood muscular dystrophy. Boys with DMD are usually confined to a wheelchair by 10 years of age and have a median life expectancy of 30 years [7]. Muscle weakness, followed by muscle and tendon retractions and joint deformities, causes gait impairment in patients with DMD, leading to compensatory movements and gait deformation. The compensatory movements occur because of the selection of possible synergic movements on hip, knees, and ankles and the development of new motor strategies used to allow the maintenance of ambulation [8].

The aim of this work is to test the efficiency of existing regression models (originally built based on data from healthy population samples) on children with disabilities. Since boys with muscular disability (and DMD in particular) perform compensatory movements to walk and have a different body mass composition, it is possible that this population requires a specific model rather than reusing normal models. Existing works have targeted studying resting energy expenditure (REE) in DMD patients and report it to be significantly lower than controls of similar population [9]. Elliott et al [10] predicted REE using existing equations based on anthropomorphic features and fat-free mass. Souza et al [11] estimated EE during ambulatory activities for a study of 3 patients using a linear formula based on heart rate.

Methods

Subjects

There were 7 subjects with DMD aged 6 to 10 years recruited from the regional neuromuscular clinic at the UC Davis Medical Center, and 6 control children and 23 healthy adults were recruited locally. Subjects completed an informed written consent approved by the Institutional Review Board of the University of California Davis.

Experimental Design

Subjects were asked to perform a series of activities in our exercise laboratory at UC Davis while being monitored by an accelerometer, a heart rate monitor, and the COSMED K4b2 (COSMED USA) metabolic system. For accelerometer measurements, we used smartphone devices placed in a waist pack and oriented in a standardized position. A chest strap was used for the heart rate monitor.

Exercise Protocol

Before each test, the COSMED K4b2 components were calibrated according to the manufacturer's instructions. Subjects were then fitted with the pack containing the phone (accelerometer) and the COSMED K4b2 metabolic system. Subjects were asked to perform the following activities, one right after the other, in the ordered listed, with approximately 1 minute rest between the walking protocols:

- 3 minutes of lying supine on an exam table
- 3 minutes of sitting
- 50-meter slow-paced walk (lasting approximately 1-2 minutes)
- 50-meter typical comfortable speed walk (45-60 sec)
- 50-meter fast walk (20-60 seconds)

Speeds were chosen based on ratings from the the OMNI scale of perceived exertion with easy walking rated as 0 to 2 or "not tired at all," medium pace as 2 to 4 or "getting a little tired," and fast walking pace as 4 to 6 or "getting more tired." The final activity was a 6-minute walking test. Cones were set up 25 meters apart in the hallway and the children walked as fast as possible back and forth between the cones for 6 minutes. Heart rate (using a Polar heart rate monitor), oxygen consumption, carbon dioxide production, respiratory exchange ratio (RER), and ventilation rate were continuously monitored.

Data from the COSMED metabolic system were averaged over the 30 to 60 seconds of each collection period. Energy expenditure was calculated using the following equation:

COSMED K4b2 EE (kcal/min)=([1.2285*RER]+3.821)*VO_2 where VO_2 is the oxygen consumption in liters per minute. All data were processed according to the following procedures:

1. COSMED output was resampled to obtain per-second estimates of EE and heart rate.

2. Smartphone sensors were oversampled at 4 Hz and then downsampled to obtain higher frequency resolution (more accurate sensor readings). Oversampling improves resolution and reduces noise in the readings. Resampling was done to obtain per-second estimates of accelerometer readings (Ax, Ay, and Az relative to the x, y, and z axis of the smartphone).

3. Accelerometer readings were synced with the COSMED readings using paper markers.

Local coordinates from the smartphone accelerometer readings were translated into global coordinates (two components: horizontal and vertical).

4. Additional information about subject measurements such as age, height, and weight were used as attributes for training data-mining algorithms and validating existing algorithms.

Machine Learning and Statistical Analysis

We used a bootstrap aggregation (bagging) ensemble technique with reduced-error pruning regression tree as the underlying classifier to predict EE [12-15]. The bagging ensemble technique is presented here because it was superior to models generated using other techniques (eg, multilayer perceptron, support vector machines, linear regression, naïve Bayes, and reduced-error pruning regression trees). The bagging technique is an ensemble meta-algorithm to improve the stability and accuracy in statistical regression obtained by regression tree. The regression tree was built using information-theoretic criterion for selecting the nodes. Once the tree is built, reduced-error pruning is used, where each node, beginning with the leaves, is replaced with its most popular class. We divided the data for the model into n=10 folds, where, n−1 folds are for supervised learning and one fold is used to test the model for errors. The the value of errors obtained in a fold is added to the weights of the nodes of the next fold in the training set. A 10-fold cross validation was used to evaluate the model in order to ensure that the model was tested on data that it had not seen while training to minimize chance for overfitting. Data processing was done in MATLAB version 8.1.0.604 (R2013a) (MathWorks), and data mining (machine-learning algorithms) was done using Weka (Waikato Environment for Knowledge Analysis) software version 3.6.10.

Existing Algorithms

We used generalized nonlinear equations [16] originally developed based on the Tritrac-R3D accelerometer and verified with Actigraph, where H and V are the horizontal and vertical accelerometer-based counts, respectively, for the k-th minute and a, b, p1, and p2 are the generalized parameters that are modeled based on the subject's gender (p1=male, p2=female) and mass in kg (Figure 1).

The resulting activity energy expenditure (EEact) is the amount of energy expended in kJ above resting energy expenditure (NOR-CHEN). For comparison with normal adults, we used a model developed from experiments on 23 healthy people. The model to estimate EE in healthy adults combined accelerometer and heart rate measurements; a protocol similar to the one outlined in this paper was followed for normal adults: obtaining sensor values and COSMED readings. In that analysis, two models were developed: one using linear regression (NOR-LIN) and the other using ensemble bagging technique over normal adults' data (NOR-ENS). Further details of the healthy adult EE study are the subject of a different paper currently under review. Based on ambulatory data collected from young controls, we develop linear (regression) and nonlinear (machine-learning–based) models for EE estimation. YOU-LIN refers to the linear regression model developed based on young controls data and YOU-ENS refers to the model built on regression trees based on reduced-error pruning.

Results

Subject Characteristics

Physical characteristics of the subjects are shown in Table 1. All subjects completed the study protocol without any problems.

Figure 1. Resulting activity energy expenditure (EEact) using generalized nonlinear equation.

$$EEact(k) = aH(k)^{p1} + bV(k)^{p2}$$

$$a = \frac{1}{1000}(12.81 \times mass(kg) + 843.22)$$

$$b = \frac{1}{1000}(38.90 \times mass(kg) - 682.44 \times gender + 692.50)$$

$$p1 = \frac{1}{1000}(2.66 \times mass(kg) + 146.72)$$

$$p2 = \frac{1}{1000}(-3.85 \times mass(kg) + 968.28)$$

Table 1. Characteristics of subjects in the study.

Attributes	DMD boys n=7 mean (SD)	Child controls n=6 mean (SD)	Adult controls n=22 mean (SD)
Age, year	8.30 (1.70)	8.58 (1.35)	37.41 (13.61)
Height, cm	121.41 (10.43)	129.40 (0.09)	170.42 (8.51)
Weight, kg	28.72 (5.84)	26.25 (4.01)	73.52 (15.32)
BMI, kg/m^2	19.32 (2.14)	15.69 (0.33)	25.14 (3.90)
Fitness: 6 min walk test, m	120.69 (16.34)	508.3 (57.5)	—

Table 2. Characteristics of the subsets of adult controls.

Characteristics	Youth mean	Middle age mean	Seniors mean
Age, years	23	34.51	54.94
Weight, kg	69	75.62	73.28
Height, cm	171.80	171.54	167.55

The adult controls were subsequently divided into three subgroups (see Table 2) to represent youth (aged 13-27 years), middle age (aged 28-50 years), and seniors (aged 50 years and older).

In our prior conference publication [17], we referred only to adult controls (n=22). The difference in population size between adults and boys with DMD could lead to potential bias, so we added control children of the same age group and divided the adult controls into three groups for comparison.

Feature Selection

The goal of feature selection is to reduce the number of attributes used in the model and understand the predictive power of the original set of attributes. Correlation feature selection (CFS) was used to identify a subset of attributes for reduction of input attributes [18]. Age; height; weight; heart rate; and horizontal, vertical, and net acceleration measurements were retained, while BMI, recovery heart rate, and 6-minute–walk test values were removed. For the CFS technique used to determine subset of important features, see Multimedia Appendix 1. Figure 2 shows the plot of information gain (IG) for all of the attributes and leads to following observations:

For boys with DMD, heart rate readings have the highest IG contribution to EE estimation. Heart rate sensor outputs give higher IG regarding EE than measures such as age, weight, height, or accelerometer values.

The IG of heart rate measurements is similar for healthy children (controls) and children with DMD, but it is lower for elder controls in our study.

The accelerometer sensor has high correlation to EE in controls across all ages but low correlation for boys with DMD. This can be attributed to restricted ambulatory movement as well as inadequacy of a single accelerometer in capturing body acceleration of boys with DMD.

The demographic variables such as height, weight, and age have low correlation to EE in healthy adults and boys with DMD but high correlation for control children. This implies that knowing the demographics of healthy children—but not boys with DMD and adult controls—is helpful to EE estimation. We may need to investigate this further with a larger population of control children.

In the DMD group, accelerometer values (net A, horizontal A, and vertical A) have lower relative information contributions for determination of overall EE compared to normal adults where accelerometer readings have higher impact than heart rate. Other factors such as age, weight, and height have small IG for both populations. The reduced predictive power of smartphone accelerometer readings can be attributed to the unique body movement of DMD patients, making it impossible for a single accelerometer to capture their body motion effectively.

Figure 2. Relative information gain of different attributes on the energy estimation.
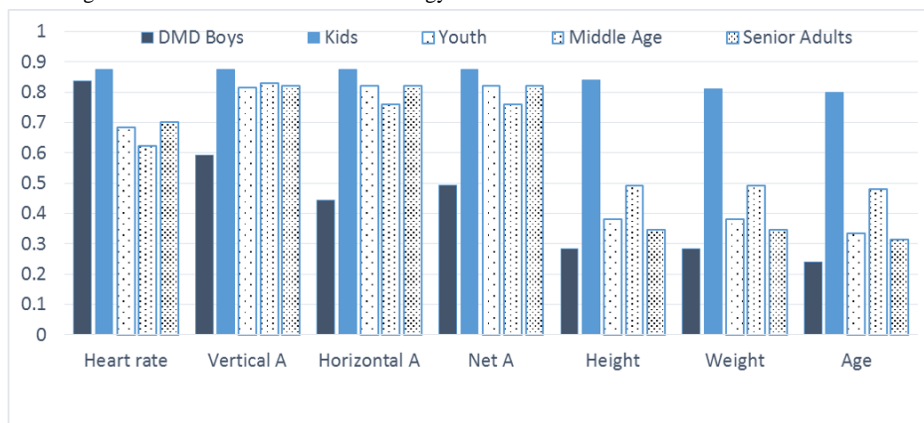
Ensemble Model

Using the data obtained from the DMD children, we identified 11 attributes (10 input features and 1 output attribute) and 7560 total instances to develop a new model of EE. The 10 input features are as follows:

- Age
- Gender
- Weight
- Net acceleration (A) of accelerometer
- Net horizontal acceleration (H) of accelerometer
- Net vertical acceleration (V) of accelerometer
- Heart rate (HR)
- Product of HR and weight (HR×W)
- Product of net acceleration with weight (A×W)
- Product of net acceleration with height (A×H)

The attribute selection algorithm, based on CFS subset evaluation and best first search [13], was used to reduce input features and select the best features. Only 5 were selected and used in final algorithm: age, HR, HR×W, A×W, and A×H. We used the bagging ensemble technique with a reduced-error pruning regression tree as the underlying regression model to predict the EE values. The regression model generated from this choice outperformed others in terms of output correlation (91.21%) and mean absolute error (0.012): neural networks (84.63%, 0.020), linear regression (81.12%, 0.019), decision stump trees (58.01%, 0.025), stacking (0.03%, 0.030), and additive regression (78.73%, 0.022). This newly developed algorithm (DMD-ENS) builds a regression tree using information variance and prunes it using reduced-error pruning (with backfitting). DMD-NOR refers to the model built over DMD population but using simple linear regression instead of ensemble technique.

## Comparison With Existing Algorithms

Results from the performance of the DMD-ENS and DMD-NOR models compared with models built over normal adults are shown in Table 3. It can be seen that existing adult models give a very poor performance (only 40% correlation) and a root mean square error (RMSE) of 0.05 to 0.75. Figure 3 gives a snapshot of EE values obtained from our ensemble model versus the actual reference values.

In our range of observations, the mean value of COSMED readings over the sample population (over 1 second epoch) was 0.09. Thus, an error of 0.03 is 33% and significant. The RMSE values are plotted in Figure 4.

Table 3. Performance comparison of DMD-ENS model with models for normal adults.

Model	Correlation to EE	Root Mean Square Error
DMD-ENS	91.20%	0.017
DMD-LIN	65.93%	0.031
NOR-CHEN [16]	40.62%	0.048
NOR-LIN	41.59%	0.051
NOR-ENS	37.91%	0.054
YOU-LIN	31.22%	0.723
YOU-ENS	46.75%	0.182

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Figure 3. Plot showing energy estimation values obtained by COSMED and those estimated by ensemble model for DMD patients.
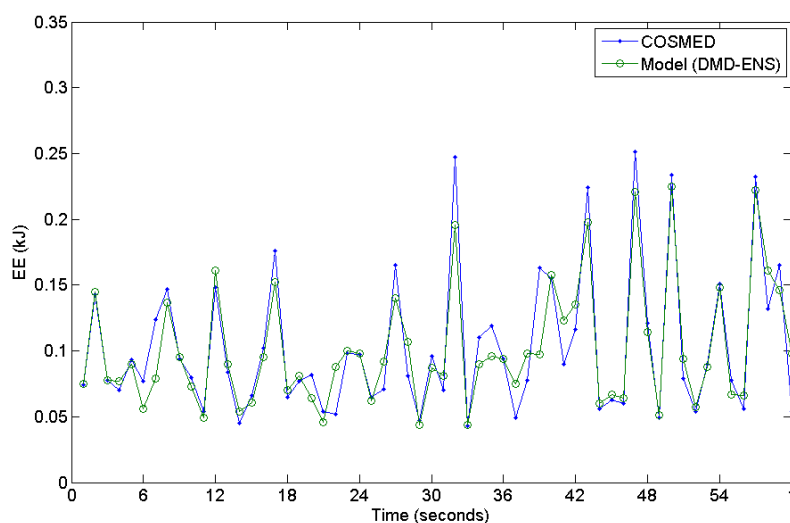
Figure 4. Bar chart showing root mean square error obtained using different models.
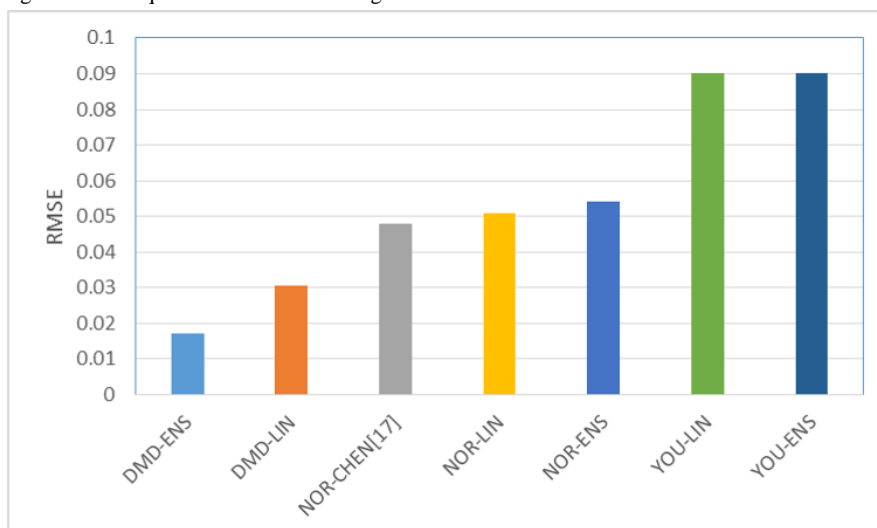
Discussion

Principle Findings

We found that existing models gave poor correlation (40%) and high error in estimating EE for children with disability. Next, we explored the role of innovative machine learning with data collected from these sensors to obtain an accurate EE model. The nonlinear machine-learning–based approach to estimate EE for children with DMD uses reduced-error pruning for regression trees with ensemble bagging models and gives high correlation (91.21%) and an RMSE of 0.017.

In this work, we explored using machine-learning techniques over data from accelerometer and heart rate sensors to obtain an accurate EE model for children with disabilities. Compared to the EE data obtained from the COSMED K4b2, EE estimation based on our proposed model (DMD-ENS) has high correlation and can be obtained by simple body-worn accelerometer and heart rate sensors, which are becoming more and more popular with new emerging wearable devices such as Fitbit, Apple Watch, and Microsoft Band. Although these devices use

proprietary algorithms, the algorithms are based on machine-learning models built for different activities of daily living [19]. In our prior work, we have shown that the machine-learning models developed in the lab can outperform these algorithms for specific ambulatory movements [20]. The poor performance of algorithms for the healthy population (only 40% correlation) indicates that these devices are not ready to use for measuring physical activity in populations with muscular dystrophy. The high correlation of a custom machine-learning model built over a dataset from children with disabilities, however, shows feasibility of developing population-specific models for EE estimation. In our future work, we would like to conduct trials over a large sample size with a larger set of ambulatory activities.

While this single model appears to work across a range of activities in a clinical setting, further investigation into the validity of this EE estimation model for daily activities outside of the clinic is needed. We observed that the existing models, developed based on adult populations, do not provide accurate levels of EE estimates. When we built regression models on

healthy children (controls), we realized that these models do not extend to children with disabilities. It is not merely the age of subjects but also their gait and other aberrations which affect EE for populations with muscular dystrophy. This confirms our assertion that population-specific models are required for EE estimation and a generic framework will not work. We also need to expand our population base to include children with other forms of muscular dystrophy to see if our proposed model scales well to those populations.

Further investigation into the bodily placement of multiple sensors will add to the information gained by sensors in specific bodily locations. Boys with DMD perform a high number of compensatory movements to walk and cover shorter distances; it would be possible to infer that using multiple accelerometers would detect such movements and this could be a confounding factor. In this study, we placed a single accelerometer sensor at the waist of the boys with DMD and found that waist acceleration is not a good predictor for EE. It is conceivable that information from multiple sensors will increase accuracy of this EE model for disabled populations depending on the particular conditions of the disability and impairment. Sensors placed on multiple body locations may be able to capture all dimensions of body motion and energy expenditure. Recent work [8] uses videotape analysis of DMD patients to develop a functional evaluation scale of gait for DMD. Sensor-based models can be used to augment functional evaluation scales in understanding progression of the disease.

Most of the participants found the sensors easy to use and unobtrusive and would be willing to wear them on a daily basis as a tool to monitor physical activity and energy balance as part of their treatment program.

Limitations

Sample size was small due to the limited size of the DMD population accessible and willing to participate in our study. We plan to continue collecting data from DMD patients to validate our results. A second limitation is that laboratory-based measurements may not correlate to regular daily activity and should be further validated in home or community settings.

Conclusion

The experiments show that machine-learning models developed for healthy populations are inaccurate for children with disabilities. An ensemble machine learning technique (bagging) based on combined accelerometer and heart rate sensor readings gave high accuracy (91.21%) to actual EE. The results are encouraging and will be useful to track energy expenditure of large patient populations in field activities.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Correlation feature selection.

[PDF File (Adobe PDF File), 29KB - rehab_v3i2e7_app1.pdf]

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Abbreviations

A×W: product of net acceleration and weight
A×H: product of net acceleration and height
CFS: correlation feature selection
DMD: Duchenne muscular dystrophy
EE: energy estimation
HR×W: product of weight and heart rate
IG: information gain
RER: respiratory exchange rate
REE: resting energy expenditure

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How Therapists Use Visualizations of Upper Limb Movement Information From Stroke Patients: A Qualitative Study With Simulated Information

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Abstract

Background: Stroke is a leading cause of disability worldwide, with upper limb deficits affecting an estimated 30% to 60% of survivors. The effectiveness of upper limb rehabilitation relies on numerous factors, particularly patient compliance to home programs and exercises set by therapists. However, therapists lack objective information about their patients' adherence to rehabilitation exercises as well as other uses of the affected arm and hand in everyday life outside the clinic. We developed a system that consists of wearable sensor technology to monitor a patient's arm movement and a Web-based dashboard to visualize this information for therapists.

Objective: The aim of our study was to evaluate how therapists use upper limb movement information visualized on a dashboard to support the rehabilitation process.

Methods: An interactive dashboard prototype with simulated movement information was created and evaluated through a user-centered design process with therapists (N=8) at a rehabilitation clinic. Data were collected through observations of therapists interacting with an interactive dashboard prototype, think-aloud data, and interviews. Data were analyzed qualitatively through thematic analysis.

Results: Therapists use visualizations of upper limb information in the following ways: (1) to obtain objective data of patients' activity levels, exercise, and neglect outside the clinic, (2) to engage patients in the rehabilitation process through education, motivation, and discussion of experiences with activities of daily living, and (3) to engage with other clinicians and researchers based on objective data. A major limitation is the lack of contextual data, which is needed by therapists to discern how movement data visualized on the dashboard relate to activities of daily living.

Conclusions: Upper limb information captured through wearable devices provides novel insights for therapists and helps to engage patients and other clinicians in therapy. Consideration needs to be given to the collection and visualization of contextual information to provide meaningful insights into patient engagement in activities of daily living. These findings open the door for further work to develop a fully functioning system and to trial it with patients and clinicians during therapy.

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KEYWORDS

stroke; upper-limb rehabilitation; therapy; information visualization; dashboard; wearable technology

Introduction

Stroke is the leading cause of acquired adult disability in high-income countries [1], with upper limb deficits affecting an estimated 30% to 60% of survivors [2,3]. Stroke causes damage within the brain that, when affecting somatosensory circuitry, lead to difficulties sensing and controlling movement of the body's contralateral side. Due to these limitations, stroke patients tend to reduce the utilization of the affected limb, which may cause muscle shortening and weakness, thus further compromising arm functionality [4]. As a result, performance in basic activities of daily living (ADL) such as eating, bathing, and dressing can be heavily affected, impacting on a patient's independence, social engagement, quality of life, and well-being [5].

Therapists (occupational therapists and physiotherapists) deliver effective upper limb rehabilitation interventions in hospitals. Interventions generally start by setting goals that target meaningful activities (eg, use of cutlery), functional movements (eg, grasp and retrieve objects), or specific impairments (eg, muscle weakness). Training is often task-specific and involves practicing tasks relevant to daily life. Along with this training, therapists employ a variety of techniques to support rehabilitation, such as mirror therapy, muscle electrical stimulation, strength training, stretching and positioning, mental practice, robotics, and virtual reality applications [4,6-8].

Since therapy time is limited, the use of the affected arm in between sessions is crucial for enhancing functional outcomes. Therapists generally prepare daily exercise routines considering a patient's personal goals, or they utilize constraint-induced movement therapy to encourage patients' use of the affected arm in daily life [4]. Although the use of activity diaries such as the Motor Activity Log (MAL) allow determining compliance with therapy when not in the clinic, these are subject to various biases including the ability and motivation of patients and caregivers to provide accurate information [9]. The lack of objective information is particularly concerning because adherence to rehabilitation programs at home is often low due to lack of motivation, musculoskeletal issues, and fatigue [10].

Wearable sensor technology offers potential to provide therapists with objective information about a patient's arm movement in everyday life. Specifically, inertial measurement units (IMUs) appear promising, because these sensors can be embedded in wristbands, gloves, or garments, and thereby track changes in the acceleration and orientation of the affected arm. Various studies in controlled settings show that IMUs can track arm, hand, and finger movements [11-14]. This line of research is typically focused on technical challenges (ie, the accuracy of motion tracking [12,15]), reliability of tracking over long periods of time [16], wearability for patients [17], and the processing of metrics from sensor data [18]. While all of these issues are important to realize the potential of wearable sensor technology, to date there has been little consideration for the needs of therapists and whether this information is useful for the rehabilitation process.

The aim of this research is to explore the information needs of therapists in order to help them understand how patients use their arm in everyday life in between rehabilitation sessions. In particular, this research seeks to address how therapists use visualizations of upper limb information presented on a dashboard to support therapy. A dashboard in this sense refers to a visual display of information on a computer screen. Similar to a car dashboard, the information on a digital dashboard needs to be compact to be monitored at a glance, to help people achieve one or more objectives [19]. Since neither wearable sensors nor dashboards are readily available, we conducted a design-driven investigation where we built a dashboard prototype that visualizes arm movement information, and we evaluated this Web-based prototype in a qualitative study with therapists. Based on a qualitative analysis we discuss the potential uses of these visualizations and identify areas for improvement.

Methods

Dashboard Design Process

The dashboard design process is part of a larger research project into the development of a system to monitor upper limb movement of stroke patients in everyday life. The envisioned system consists of (1) wearable sensor technology that patients wear on their arm over several weeks to monitor upper limb data in everyday life; and (2) a dashboard to present the sensor data to therapists for use in consultations with patients.

A wearable sensor prototype has been evaluated in a movement laboratory to establish the feasibility of this approach [20]. The prototype captures motion of the arm through IMUs placed at the wrist, above the elbow, and at the shoulder. From these sensors, motions in three degrees of freedom in the shoulder (adduction/adduction, flexion/extension, internal/external rotation), one in the elbow (flexion/extension), and one in the wrist (pronation/supination) can be calculated. The current system is not capable of capturing wrist extension or finger movements. The project team is now working on a sensor prototype that is comfortable to wear and robust enough for use in everyday life.

We designed a dashboard prototype that visualizes sensor data to support therapists in their consultations with patients. The prototype was created through a user-centered design process, a standard approach in the field of human-computer interaction, to ensure that the dashboard that is being developed meets the needs of users [19,21]. The design process started with informal interviews with 3 occupational therapists (OTs) to understand the problems faced by therapists and the need for objective information. Based on these insights, 3 rounds of design workshops were conducted to generate and review ideas for information and visualizations that could be useful to support the work of therapists. These workshops involved 2 OTs, 1

physiotherapist, 2 mechanical engineers, 2 experts on wearable technology, and 2 interaction design researchers. As is common in a user-centered design process [22], ideas were initially sketched on paper for review and discussion. For the second and third workshops these sketches were refined as paper prototypes and digital prototypes. The final dashboard prototype was built with the prototyping software Axure, which supports the implementation of interactive Web-based prototypes without requiring software development skills. The strengths of such a prototyping approach are that they capture the key ideas of the entire team, allow quick evaluation and iteration, and facilitate discussion about relevant information and visualizations before effort is spent on developing the actual software [22,23].

Dashboard Prototype

We developed an interactive dashboard prototype to gather feedback from therapists on the usefulness of various upper limb visualizations before a fully functioning system is implemented. As illustrated in the following figures, the prototype was designed in a sketchy manner to invite feedback, and to avoid giving the impression that this was a fully functioning website.

The dashboard prototype evaluated in this study contained upper limb movement information for each patient (Textbox 1).

This information was based on interviews and design workshops with therapists, as well as related work on kinematic measures for upper limb movements [18]. Related work shows that inertial sensors can provide information on the amount of arm movement and time spent using the arm in daily life [24]. Quality of movement and range of motion (ROM) are typically generated through robotic technologies or opto-electronic systems [18]. These systems can provide more precise measurements than inertial sensors, but they rely on a controlled environment and hence are not readily available for daily life use.

Part of the information displayed on the website was based on sensor data collected in a movement laboratory [20]. We created additional fictional information in consultation with therapists to ensure that the information presented on the dashboard is complete and realistic for a stroke patient.

The following figures show how this information was presented on the dashboard through 5 screens, which support different views and analysis of the various data.

Overview Page

The first page provides an overview of a patient's upper limb information (Figure 1). It includes a brief patient profile, showing age, affected arm, dominant arm, and date of incident. An overview is provided of key movement information, including a tabular summary of number of movements overall, quality of movement, and time active. The therapists in the design workshops wanted both information about averages and for particular time periods. Furthermore, a timeline shows the number of movements over the last week, and the quality of movement on a scale from 1 (low quality) to 10 (high quality). The visualizations here were inspired by related work [19] and commercial dashboards of activity trackers (eg, Fitbit, Jawbone Up). Therapists can add notes. This is important as patients are usually seen by multiple therapists in the course of their therapy.

Textbox 1. Upper limb information for each patient.

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1. Amount of arm movement, counting movements for each degree of freedom.

2. Time spent using the arm.

3. Quality of movement (as indicated by compensatory movements, speed, and smoothness), on a scale from 1 to 10.

4. Range of motion (ROM) for each degree of freedom.

5. A list of the above information for each detected movement.


Figure 1. Screenshot of the overview page.
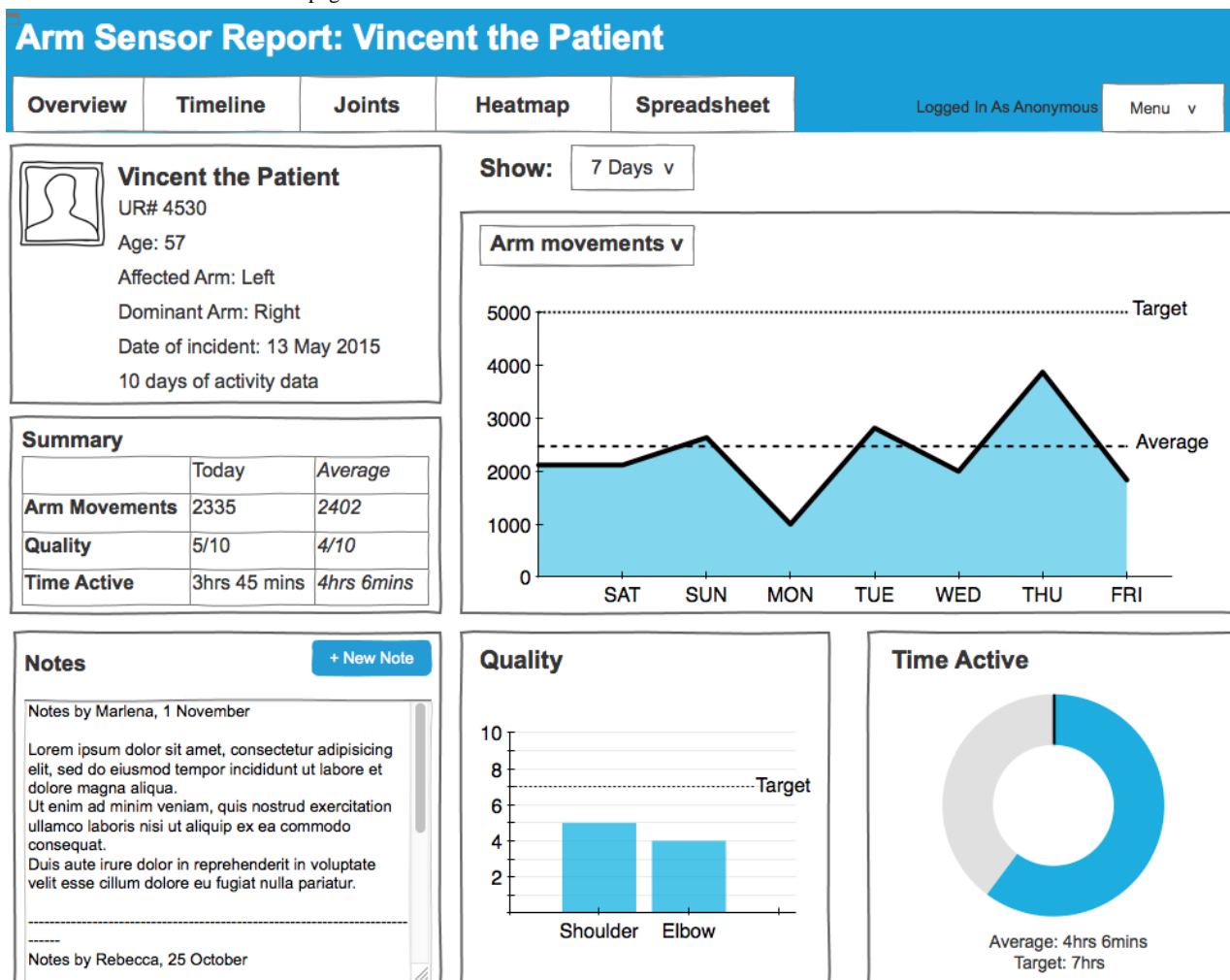
Timeline Page

The timeline page, which provides detailed movement information at two different time scales is shown in Figure 2. The timeline on the top presents movement patterns over long periods of time, from several hours to several days. The data presented here shows the level of activity, for example, 50% means that the arm is moved for 5 minutes during a 10- minute window. This information was included to provide therapists with a quick snapshot of how active patients are throughout a day. Therapists can annotate this data by dragging and dropping tags like "exercising" and "eating" to the activity timeline.

The timeline on the bottom of the page presents movement for each degree of freedom over several seconds. The red progress bar connects the two time lines. This information was included so that therapists can explore movement in more detail and obtain insights into the quality of movement. For example, they can select a data point in the activity timeline (on top of the page) from a period of exercising, and on the bottom of the page they can see how the exercise was performed (eg, whether the movement was initiated by abducting from the shoulder which would indicate a compensatory movement). A media player (bottom right) shows arm position and movement corresponding to the progress bar on the time line to visualize how the arm moves to aid with this analysis.

Figure 2. Screenshot of the timeline page.
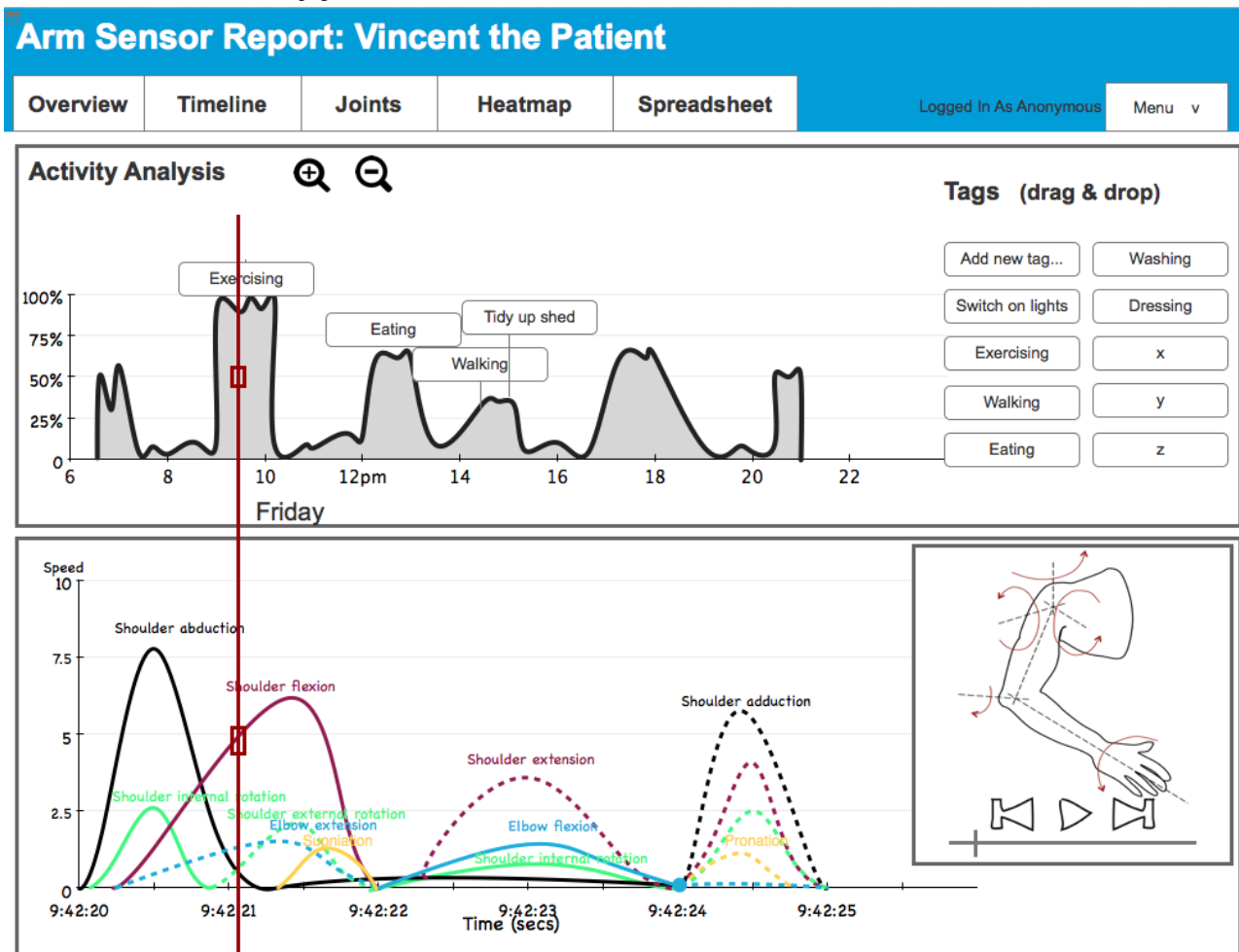
Joints Page

The joint-based visualization illustrated in Figure 3 structures movement information around the entire arm. Therapists can click on a particular plane of movement in each joint (eg, shoulder abduction/adduction) to access a summary of a number of movements, quality, time active, and active ROM for the selected movement. Inspired by related work [25], the ROM is further illustrated for the selected joint through an avatar that visualizes the ROM achieved by the patient in daily life compared with the maximum ROM possible for this type of movement. This page was developed during the design workshops to show patients how the information collected through sensors relates to the different types of upper limb movement.

Figure 3. Screenshot of the joints page.
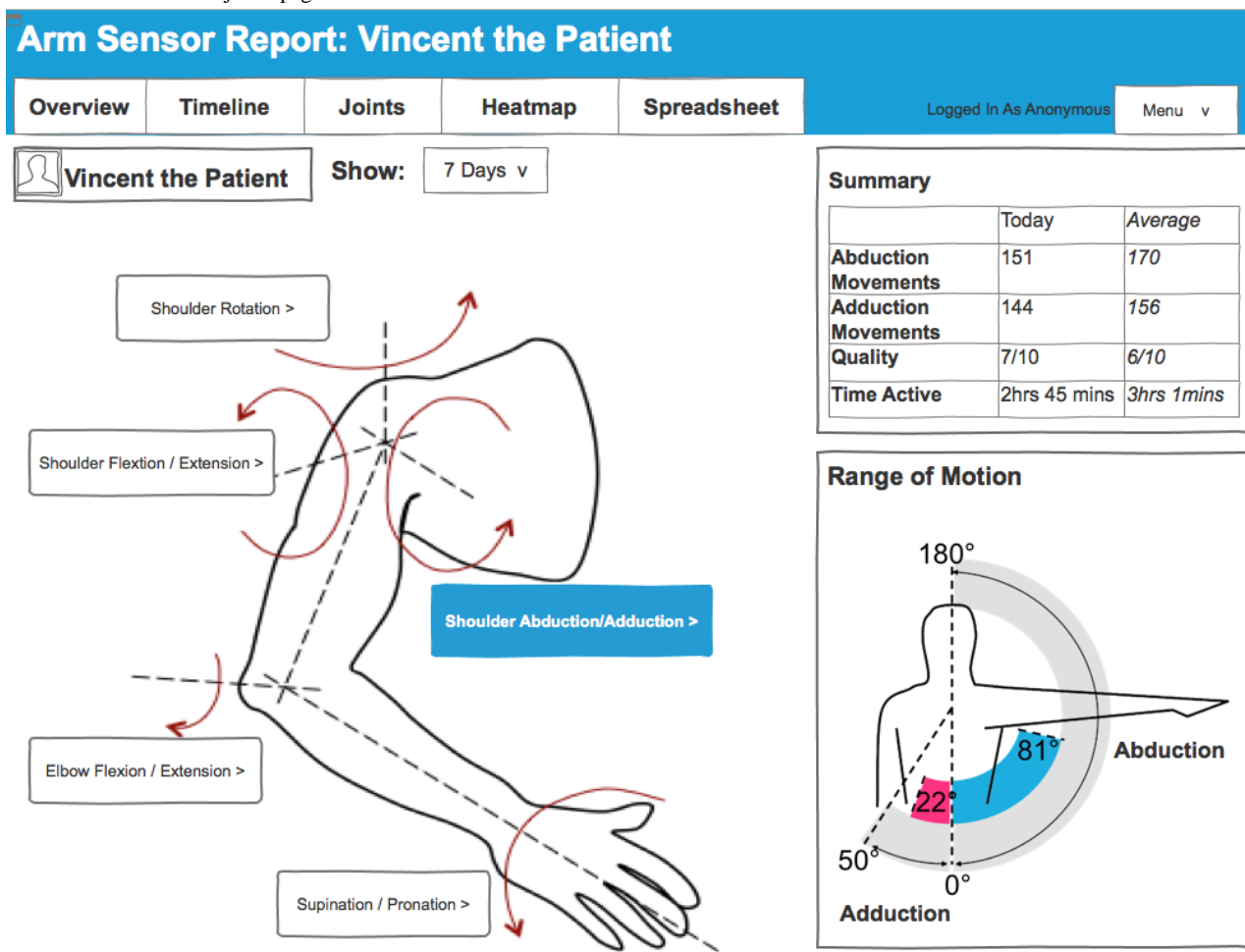
Heatmap Page

Figure 4 presents the heatmap page, which shows common movement (top) and common static positions (bottom) of the affected hand over the last 7 days. Areas in red show the most common movements or positions, where green and blue indicate some movement or positioning, whereas white indicates areas which were not reached by the hand in the 7-day period. The front view (left) shows whether the hand has crossed the midline, whereas the side view indicates whether patient have the capability to reach forward. Heatmaps are incorporated in the dashboard because therapists and patients are already familiar with this type of visualization from computer-based therapy games (AbleX system) used in the hospital.

Figure 4. Screenshot of the heatmap page.

Spreadsheet Page

Figure 5 shows the spreadsheet, which allows therapists to inspect all movements captured by the sensor and to sort them by time, quality, duration, and range of motion. A media player can be used to illustrate the arm movement selected in the spreadsheet. The data can be exported for further analysis (eg, for research into the effectiveness of interventions). This page was included during the design workshops to provide support detailed analysis of movements for therapists engaged in research activities.

Figure 5. Screenshot of the spreadsheet page. ROM: range of motion.
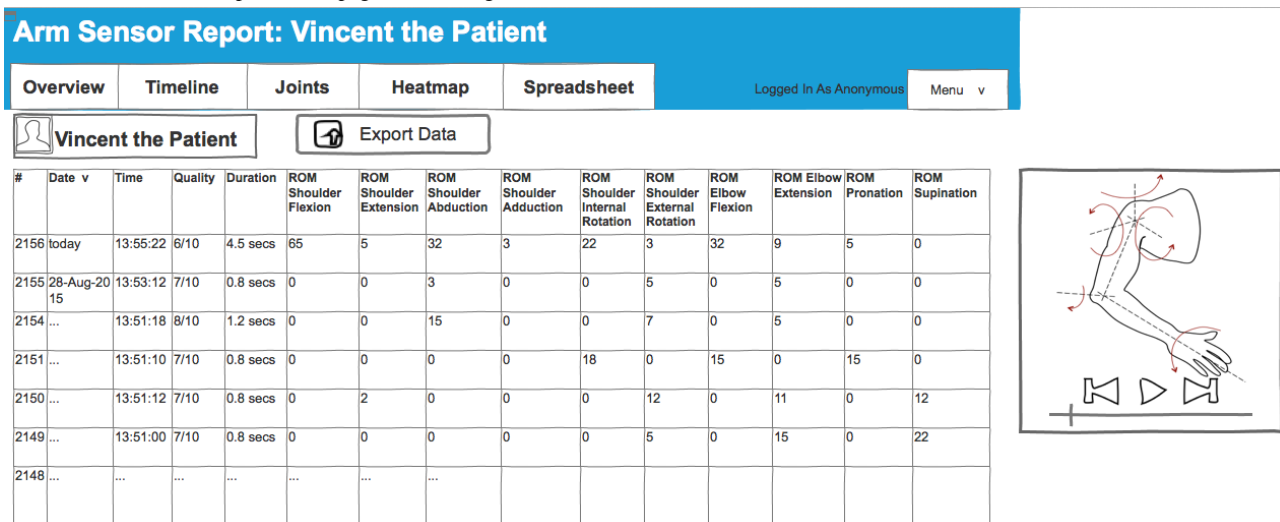
Study Participants

We recruited 8 therapists (all female) to evaluate the dashboard prototype. Participants were recruited through the Royal Melbourne Hospital, Australia. All therapists were actively engaged in upper limb therapy with patients with neurological conditions including stroke, multiple sclerosis, traumatic brain injuries, and Parkinson's disease. Their clinical experience ranged from 3 months to 12 years. Five therapists worked predominantly with acute patients (within the first few weeks after presenting to hospital) and 3 therapists worked with chronic patients (ranging from several weeks to several years after a stroke). These 8 therapists had not been involved in the design process. They were recruited for the evaluation to provide unbiased feedback on the dashboard. Book vouchers were offered to participants for their time and involvement in the dashboard evaluation.

Dashboard Evaluation

A qualitative evaluation was conducted to explore how therapists would use the information presented and visualized on the dashboard. The evaluations took place in a meeting room at the hospital and lasted 60 minutes per therapist. Ethics approval was obtained through the University of Melbourne (#1545866).

The evaluation followed a standard procedure. First, a background interview was conducted to learn about upper limb rehabilitation practices and the information therapists desire about their patients. Second, we conducted observations of therapists exploring each of the 5 dashboard pages. The therapists were instructed to think aloud in order to get a better understanding about their impressions of each visualization on the website and any questions or expectations that they may have. Finally, through a semi-structured interview, the therapists were asked to compare and rate the 5 visualizations in terms of usefulness for their work with stroke patients. These ratings were used as prompts to discuss how the dashboard could be integrated with their current work practices and the potential impact on improving rehabilitation outcomes.

Each evaluation was audio-recorded and transcribed for later analysis. The examination of the dashboard was also screen-recorded with input from a webcam to capture facial expression of participants as they interacted with the website.

The data were analyzed qualitatively, following a thematic analysis approach [26]. The authors read through all transcripts and coded the data to identify the various uses for each visualization as well as areas for improvement. Data were coded by the authors (BP, JF, SN) through SaturateApp, a Web-based tool for collaborative qualitative analysis. In total, 249 codes were generated about the uses for the 5 dashboard pages, 35 codes about ranking the different visualizations according to their potential usefulness, and 55 codes about the usefulness of the dashboard as a whole. In consultation with the research team these codes were collated into 3 themes that describe the uses of the dashboard and 1 theme about a major limitation in using the system, which are presented next.

Results

Theme 1: Objective Data About Activity Levels, Exercise, and Neglect

The main use of the dashboard is to obtain objective patient data. Therapists can glance at the dashboard before or during consultations to assess how patients engage their upper limb outside the clinic including how actively they engage the affected limb, their adherence to exercise regimens, and possible neglect of the affected limb.

The overview page was preferred by 63% (5/8) of therapists to assess the activity levels of patients outside the clinic. The overview page provides a quick snapshot of the patient's activity levels through visualizations of the number of movements performed over a week, the average quality of these movements, and the time spent active for each day. A simple timeline showing movements performed over a week offers therapists a quick glance of days when their patients performed well and when their patients did not reach their target levels.

> *A lot of patients will try really hard today, and then tomorrow they really suffer, and then the next day they will probably do somewhere in between, and then two days later they will be like "oh I haven't*

done my exercises very much." And educating a patient around that when you've got hard data spike is really valuable. [OT8]

The timeline page was preferred to assess whether patients adhered to the prescribed exercise regimens. The first visualization on this page shows the times and the intensity of arm activities over several days. Therapists used this information to infer activities based on time (eg, eating), duration (eg, exercise), or through conversation with patients. Some patients keep exercise diaries that therapists can use to compare with the timeline data. The timeline supports tagging, meaning that therapists can manually annotate events on the timeline with labels such as exercising and eating. It is important to note that the second timeline on the bottom of this page was not considered useful. This timeline would support analysis of movements for each degree of freedom over several seconds, for example, to inspect how patients perform an exercise. However, therapists commented that they would not have the time to analyze the data in this way.

If you're worried that he's not doing his exercises, or he's not incorporating his hand when he's eating, well this would somewhat tell you whether there's a flat line or whether there are moments of activity. [OT5]

We could get them to keep a diary or something like that, and when they come then sit down with their diary. I like the idea there is some sort of analysis of the activities even though you have to look at each patient and think about if it's accurate or not. [OT3]

We work on a busy rehab ward, would we actually come back to this and really analyze [the second timeline on the bottom of the page] to every five seconds? [OT5]

Finally, therapists found the heatmaps useful to assess patients with very low levels of mobility and patients with hemispatial neglect, who have difficulty attending to one side of space. The heatmaps indicate where the hand is resting, and can be used to identify whether the hand is resting in a "natural" position. The heatmaps also show whether the hand of the patient crosses the midline of their body. This indicates attendance to the neglected side in neglect patients, and it shows an increased range of activities of daily living that a patient is able to perform.

You want to know when they're sitting particularly the ones that have neglect, do they just leave it dangling down here, or are they positioning it in an appropriate way? I like that. It's good. [OT4]

If you can cross midline and do stuff you are getting better plasticity showing but you're also functionally significantly more independent than if you can only work here. [OT8]

Theme 2: Engage Patients to Learn About Therapy, Provide Motivation, and Reflect on Progress

A second area of use for the dashboard is to engage patients in a dialogue about the data to become more actively involved in the rehabilitation process. Therapists and patients can collaboratively examine the data presented on the dashboard to foster motivation and to inquire how patients cope in their everyday life.

Particularly the timeline data and the tagging feature invited opportunities for therapists to engage their patients to learn more about exercise and other activities. Therapists can use the data to inquire about how well patients cope with the exercise programs that they have been given. Therapists may also use peaks and troughs in the timeline data to ask more broadly about the well-being of their patients in daily life.

I'd sit down with the patient and ask what they were doing between 8am and 10am on Friday, and they say they went to the gym. So I put in exercise. [OT3]

Are they coping with what I've given them? If they're not doing their exercises, why? [OT7]

Furthermore, therapists used the dashboard (ie, the ROM presented on the joints page) to educate and motivate patients. Therapists wanted to use the data to teach patients how the arm works, what their capabilities are, and to discuss how they are progressing. Improvements in the ROM are not always visible to patients and therapists, and therapists typically do not have the time to assess ROM with a goniometer in each therapy session. Seeing progress in ROM through the joints page, however, was useful to see how patients progress over the course of a therapy as well as to detect discrepancies between how patients perform in therapy and how they perform at home. ROM is also an important indicator of the activities of daily living that a patient is able to perform. For example, activities like feeding require a certain range of motion to extend the elbow and to supinate at the wrist. Hence, based on the information about the ROM displayed in the joints section therapists and patients discuss their goals.

It would be nice to be able to give the patients this feedback and show them visually how they are doing, and be able to say "this is where we want you to be. This is your target for the next 2 weeks." And then you could be pushing that target out as they improve. [OT1]

It's going to help me visualize their movement. If I know that they can only get to 181° for the certain task that they pick during the day, you can sort of know how they would perform it. And it also gives us goals to work on, to increase that range of movement. [OT4]

Finally, therapists found the visualizations on the overview page and the heatmaps useful to engage patients in discussion about the rehabilitation progress. The overview page provides simple visualizations of the number of movements carried out by a patient that can illustrate improvements and thereby motivate patients to adhere to their exercise regimens and goals. Heatmaps, on the other hand, are useful to engage patients in discussions about which areas they need to target when moving their arm. Some therapists emphasized that the dashboard provides a useful, additional voice to the therapy that motivates patients.

I use that in two senses - to provide patients with motivation and say they've improved a little more this

week; and the flip side is if they're not improving I provide realistic feedback so in three weeks' time, when I discharge them from the service and they're 'my arm hasn't improved', it's not a shock to them. [OT3]

If it [the heatmap] was all just red by his body I could talk to him about it's really important to let that arm sit down and extend the elbow to involve it one day in swinging while he's walking. [OT2]

I think it's quite motivating for patients. It's not just me speaking to them. [OT7]

Theme 3: Engage With Other Clinicians and Researchers Based on Objective Data

The information presented on the dashboard can also be useful beyond the interactions between a therapist and a patient during therapy. It provides therapists with objective data to advocate for patients in interactions with other clinicians. For example, providing evidence about improvements in the range of motion in everyday life can help to persuade other clinicians about the importance of upper limb therapy. Objective data is useful here, because therapists often rely on subjective judgments about a patient's ability to participate in activities of daily living, and such judgments are difficult to translate between health professionals. Both forms of evidence are important to advocate for patients to receive adequate resources required for rehabilitation.

Other therapists, your physio colleagues, or your doctors, they can actually see that the patient's arm movement is improving. So if they started off with no movement at the shoulder whatsoever, but three weeks down the track they're actually generating some active movement. [OT5]

Being able to show other team members what movements are improving, and the doctors as well, it would be awesome to take this data to a team meeting and to show how much a patient has improved from a movement point of view. Because often what we are doing is advocate for rehab. And not every patient gets the rehab. If we can show to the team that they made all these improvements in terms of arm function, our case would be so much stronger. [OT1]

Finally, the information available through the dashboard provides opportunities for research into the effectiveness of rehabilitation services provided at the clinic. The spreadsheet page allows therapists to sort data by time, duration, and quality to support detailed analysis of the motions performed by individual patients. While the spreadsheet page was not considered useful for therapy, being able to export this data was seen as useful for further therapists engaged in research activities in order to assess the effectiveness of interventions across different patients.

Your spreadsheet is only helpful for data analysis and research, which I think is a great thing to have incorporated but there's only going to be a small group of people that would utilize that. [OT8]

Theme 4: Contextual Information is Critical to Analyze Movement Data

A major limitation is the lack of contextual information presented across the different dashboard pages. The different dashboard pages presented various movement data (number, range, duration, quality of movement). However, a recurring discussion point with therapists was the lack of contextual information to understand the significance of these movements in daily life.

First, the lack of contextual information was evident in discussions of the quality ratings. The quality rating was displayed on the overview page as an average value between 1 and 10 for all the movements performed over the course of a day, thus allowing the therapists to see trends in the data over several days and weeks. The therapists confirmed the findings from study 1 that information about the quality of the movements outside the clinic is critical, for some even more so than the number of movements. However, while the therapists desired a quality score, they also felt that in order to truly judge the quality of a movement they would have to see their patient making the movement. This is because the quality of a movement is dependent on its purpose in a particular context. For example, lifting the shoulder and shoulder abduction are often used as indicators for low quality movements, because many stroke patients use these movements to compensate for difficulties in reaching forward, or involuntarily abduct the shoulder when intending to reach forward. However, in certain contexts lifting the shoulder and abduction can be desirable and indicative of a normal, high quality movement, which cannot be distinguished by the system.

It is important that they do their activities well, not just a lot. [OT1]

I have some questions about measuring this one, quality. This doesn't have any way to determine the movements are of quality and whether they're normal or not, it's just detecting [motion] - for some tasks a quality movement would be to abduct your arm like this so you bring your hand up to do your hair, and for reaching to abduct your arm isn't a normal movement. So if you're able to measure abduction but then you're not able to know what the task is they're doing, how do you determine whether that's a quality movement for that task? [OT3]

Second, the lack of contextual information was evident in discussions about the timeline page. Based on the dashboard alone therapists cannot know if a movement constitutes an exercise activity, if the patient is engaging in an activity of daily living like eating, if the arm is swinging while walking, or if the arm is moved by a caretaker who helps the patient get dressed. The timeline presents some contextual information through the time of the day when movements are performed, which can indicate that a patient is eating or washing. However, the precise nature of the activity needs to be confirmed in conversation with a patient.

I find it really hard because you don't know what they're doing when they're doing this movement. Like I could be walking, going like this, and that's going

to be counting the movement of every joint whereas it's not specifically functional. [OT4]

The lack of contextual information provides opportunities for encouraging participation by patients. On the one hand, therapists commented that some patients would be interested in collecting contextual information, for example, through a mobile app that would help them to diarize events. On the other hand, the lack of contextual information provides an opportunity for increased patient participation during consultations through dialogue about the data. Patients contribute their lived experience and therapists their domain knowledge to collectively interpret the data.

For patients that were more technologically savvy you could do something like getting them to write down at the end of the day what it is that they've done, and I think with some of the more cognitively impaired or older patients, that would be really difficult for them to reflect back on "what did I do yesterday at different times of the day?" So that's why I think having something to support it, like a time use diary or a written diary or a phone app, would be really useful. [OT6]

We can actually show them the days that they are doing better, and actually talk about, let's say "Monday wasn't so good", maybe they had a lot of scans and investigations. Or maybe they had a really bad day and didn't want to do their rehab. [OT1]

Discussion

Principal Findings

This research identified core principles for the visualization of information collected through wearable sensor technologies for use by occupational therapists.

Dashboards provide objective data for therapists about the activities of patients outside the clinic. This is important because prior work shows that the quality of subjective data through retrospective recall and exercise diaries is limited, and it relies on patients who are motivated and have adequate cognition [9]. Hence, data from wearable devices presented on the dashboard can verify subjective accounts from patients through objective data about activity levels in between therapy sessions, exercises performed at home, and attendance to the neglected side of the body.

In accessing objective data, therapists emphasized the importance of getting an overview, over being able to see details. In line with the principal idea of a dashboard [19], the overview needs to provide a quick glance of the patient data. This overview needs to support comparison between different timescales, from several hours to several weeks, and between different joint movements (eg, to compare shoulder abduction with shoulder flexion). Unlike in other domains [27], the therapists expressed that they would not have time to inspect details of individual movements or outliers in the data, because it would take time away from working hands-on with patients. Hence the spreadsheet and the detailed timeline to analyze movements over several seconds were seen as superfluous.

Visualizations need to engage patients in the therapy process. In particular, visualizations play an important role in discussing progress, motivating patients, and prompting reflection about exercises and activities of daily living performed in their own homes. Timeline visualizations were useful to discuss progress with patients. Heatmaps were useful to present spatial information about common positions and postures of the arm for reflection with patients. This is important to foster patient participation and motivation to achieve positive rehabilitation outcomes [28].

Visualizations and objective data are important to help therapists advocate on behalf of their patients in discussions with other clinicians. The work of therapists depends to a large extent on subjective judgments about a patient's ability to engage in activities of daily living. Hence, having objective movement data captured in daily life provides an objective indicator of a patient's capabilities that therapists can use in discussions with other clinicians.

Contextual information is critical to analyze the information visualized on the dashboard. The lack of contextual information was raised as a key limitation because the therapists wanted to understand how much patients use their affected upper limb in daily life outside therapy (eg, to exercise, eat, or dress themselves). There was a disparity between the generally hands-on work of therapists, where they can touch and observe patients and understand the intentions of their actions, and the visualizations generated from sensor data that were disembodied and lacked references to the settings in which movements occur. Prior work on clinicians interpreting sensor data from patients with Parkinson's disease [29] and multiple sclerosis [30] highlights similar challenges in interpreting sensor data where therapists find it difficult to interpret sensor data in the absence of the patient, even though these studies [29,30] used sensors for short assessments in clinical settings, rather than to collect data over days and weeks in real-life. Health data are often not self-evident, and additional work is required to make sense of the data and to apply it in practice [29,31]. However contextual information is particularly important for therapists to interpret body movement, including understanding how movements relate to activities of daily living ranging from personal and domestic tasks, to community, employment, leisure, and recreational activities [32]. Hence, subsequent phases of this project will explore how contextual information can be gathered, such as through sensors embedded in objects and places that indicate activities (like sensors embedded in cutlery to indicate eating), or through mobile apps that allow patients or their caretakers to annotate movement information with pictures or personal notes about daily life activities. Furthermore, we seek to investigate to what extent the revised dashboard can elicit contextual information through dialogue between patients and therapists.

Figure 6 summarizes the findings through a revised dashboard design. Based on the results presented above we combined the most useful elements of the 5 original dashboard pages into a design that fits on a single page to support meaningful comparison and minimize time spent navigating the dashboard. The annotations to Figure 6 summarize the key findings about the uses of the dashboard (obtain objective data, and to engage

patients and clinicians) and the areas identified for improvement (capture contextual information, changes to enhance the clarity of the information presented, and content omitted due to lack of use).

Figure 6. Revised dashboard design based on the findings from this study. The annotations on the left side show how the new design maintains the key features that the therapists found useful. The annotations on the right side highlight changes to the design.
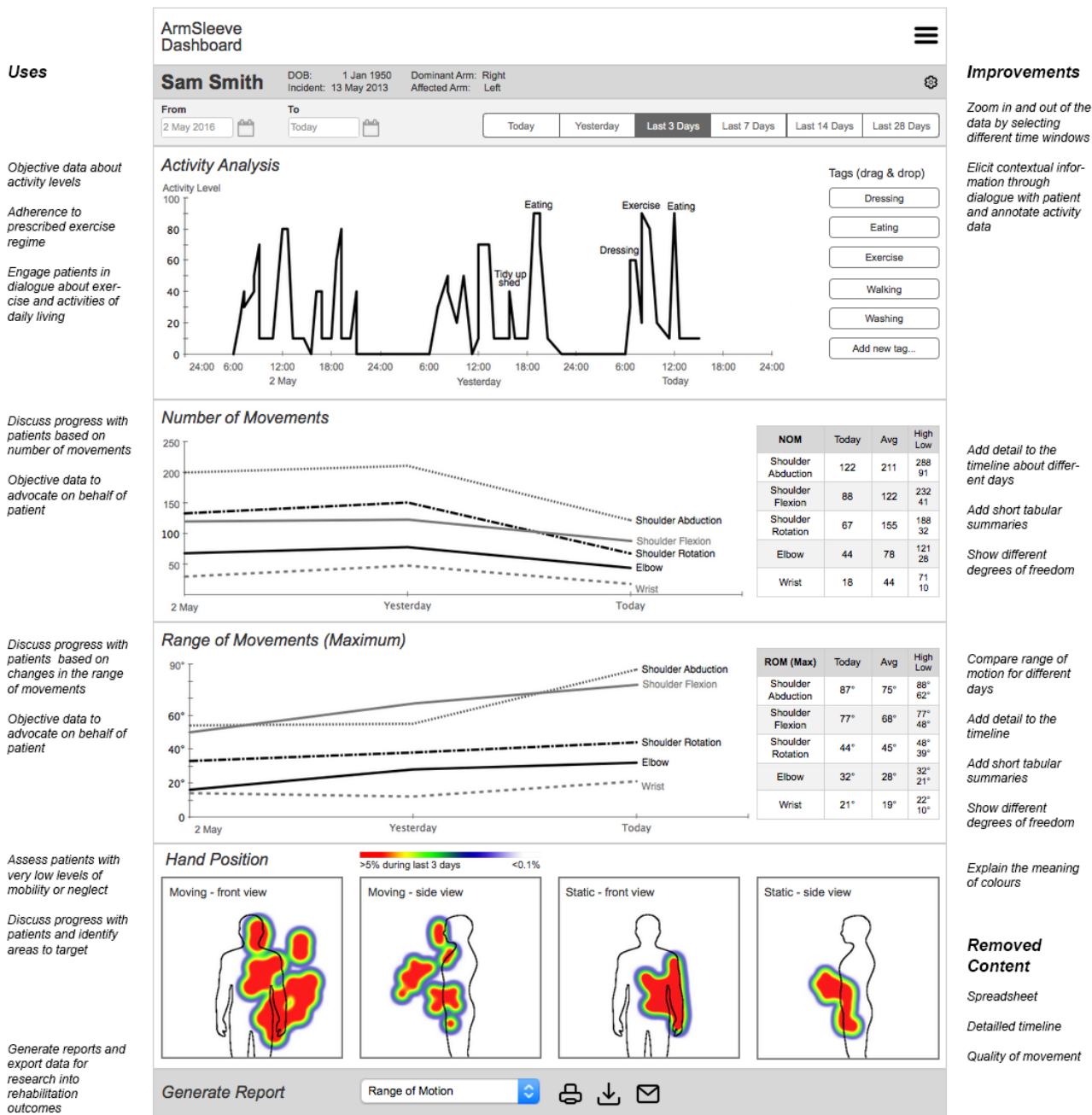
Limitations

The main limitation of this study lies in the ecological validity. The findings of this study provide rich insights into the potential uses of a dashboard to support upper limb therapy. However, evaluations in a laboratory or simulated setting do not allow for evaluation of how a system would be used in a real-world setting and how it fits into the work practices of therapists. Furthermore, the prototype relied on mock data because real-life data about upper limb movement over extended periods of time is currently not available. If real-life sensor data were available, it is likely that the data would contain a degree of inaccuracy due to movement of the sensors on the patient's body and due to sensor drift, which would affect measures of quality and range of motion. Finally, the therapists in this study spoke about the potential uses of the dashboard to engage patients, yet these claims have not been verified with patients. A deployment study of a functioning dashboard and wearable technology with patients engaged in upper limb therapy and their therapists will be conducted in the next phase of this project to address these limitations.

A further limitation of the dashboard and wearable technology developed in this project is the lack of data on wrist and finger extension. The current system focusses on the movement of the arm (shoulder, elbow, and wrist supination/pronation), which

is critical for many stroke patients with low levels of mobility. However, activities of daily living like eating, dressing, and washing rely to a great extent on our ability to move the wrist and the fingers, which are not captured in the current design. Related work shows the potential of capturing finger and wrist movements through sensors captured through gloves [33,34] or rings worn on the finger [12,16], which we aim to explore in subsequent phases of this research project.

Conclusions

Upper limb information from wearable technology provides hitherto unavailable insights into the activities of stroke patients outside the clinic. Visualization of this information provides therapists with objective data, engages patients and supports discussion with other clinicians. Consideration needs to be given to contextual information, such as how to collect this information and how to integrate it with existing visualizations to provide meaningful insights into activities of daily living performed by patients. These findings open the door for further work to develop wearable technology for patients to collect upper limb data in real life, and to develop visualizations that present this information to therapists and patients to support rehabilitation.

Authors' Contributions

This research project has been conceptualized and led by MPG, BP, and FV. BP and JF designed the dashboard prototype with clinical input from MK and ECL. The study has been designed and conducted by BP, JF, and SN. The paper was drafted by BP. All authors took part in editing this paper.

Conflicts of Interest

None declared.

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Abbreviations

ADL: activities of daily living
CIMT: constraint-induced movement therapy
IMUs: inertial measurement units
MAL: Motor Activity Log
ROM: range of motion

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Original Paper

A Personalized Self-Management Rehabilitation System for Stroke Survivors: A Quantitative Gait Analysis Using a Smart Insole

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Abstract

Background: In the United Kingdom, stroke is the single largest cause of adult disability and results in a cost to the economy of £8.9 billion per annum. Service needs are currently not being met; therefore, initiatives that focus on patient-centered care that promote long-term self-management for chronic conditions should be at the forefront of service redesign. The use of innovative technologies and the ability to apply these effectively to promote behavior change are paramount in meeting the current challenges.

Objective: Our objective was to gain a deeper insight into the impact of innovative technologies in support of home-based, self-managed rehabilitation for stroke survivors. An intervention of daily walks can assist with improving lower limb motor function, and this can be measured by using technology. This paper focuses on assessing the usage of self-management technologies on poststroke survivors while undergoing rehabilitation at home.

Methods: A realist evaluation of a personalized self-management rehabilitation system was undertaken in the homes of stroke survivors (N=5) over a period of approximately two months. Context, mechanisms, and outcomes were developed and explored using theories relating to motor recovery. Participants were encouraged to self-manage their daily walking activity; this was achieved through goal setting and motivational feedback. Gait data were collected and analyzed to produce metrics such as speed, heel strikes, and symmetry. This was achieved using a "smart insole" to facilitate measurement of walking activities in a free-living, nonrestrictive environment.

Results: Initial findings indicated that 4 out of 5 participants performed better during the second half of the evaluation. Performance increase was evident through improved heel strikes on participants' affected limb. Additionally, increase in performance in relation to speed was also evident for all 5 participants. A common strategy emerged across all but one participant as symmetry performance was sacrificed in favor of improved heel strikes. This paper evaluates compliance and intensity of use.

Conclusion: Our findings suggested that 4 out of the 5 participants improved their ability to heel strike on their affected limb. All participants showed improvements in their speed of gait measured in steps per minute with an average increase of 9.8% during the rehabilitation program. Performance in relation to symmetry showed an 8.5% average decline across participants, although 1 participant improved by 4%. Context, mechanism, and outcomes indicated that dual motor learning and compensatory strategies were deployed by the participants.

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KEYWORDS

ambulatory monitoring; gait; rehabilitation; self-management; smart insole; stroke

Introduction

The global incidence of stroke is set to escalate from 15.3 million to 23 million by 2030 [1]. In the United Kingdom, stroke is the largest cause of disability [2] resulting in a cost to the economy of £8.9 billion a year [3]. It is estimated that following a stroke, only 15% of people will gain complete recovery for both the upper and lower extremities [4]. Walking and mobility are prominent challenges for many survivors who report the importance of mobility therapy [5]. Nevertheless, rehabilitative service needs cannot always be met and therefore initiatives that focus on patient-centered care promoting long-term self-management remain at the forefront of service redesign [6].

The adoption of technological solutions allows for patient and carer empowerment and a paradigm shift in control and decision-making to one of a shared responsibility. It also has the potential to reduce the burden for care professionals, and support the development of new interventions [7]. Incorporating technology into the daily lives of stroke survivors can be achieved by maintaining high levels of usability, acceptance, engagement, and removing any associated stigma involved with the use of assistive technology [8].

Technological aids for poststroke motor recovery hitherto have required the use of expensive, complex, and cumbersome apparatus that have typically necessitated the therapist to be present during use [9,10]. Recently, inexpensive, wearable, commercially-available sensors have become a more viable option for independent home-based poststroke rehabilitation [11,12]. A systematic review by Powell et al [13] identified a number of wearable lower-limb devices that have been trialed, such as robotics [14-16], virtual reality [16], functional electrical stimulation (FES) [17,18], electromyographic biofeedback (EMG-BFB) [19,20], and transcutaneous electrical nerve stimulation [21]. Of the identified trials exploring improvements in the International Classification of Functioning (ICF) domain of activities and participation, only 1 [21] found significant improvements. Studies that adopt a positivist randomized controlled trial paradigm often fail to give sufficient consideration as to how intervention components interact [22]. Indeed, creating and developing technological solutions for complex long-term conditions is challenging and requires multiple stakeholder input [23].

The Self-management supported by Assistive, Rehabilitation and Telecare Technologies consortium explored rehabilitation for stroke survivors focusing initially on the use of wearable sensors to support upper limb feedback on the achievement of functional goals [24-30]. User interface design, the practicalities surrounding deployment, and the ability of the participants to interact with the technology were explored [24].

The intervention model for the stroke system was based around a rehabilitation paradigm underpinned by theories of motor relearning and neuroplastic adaptation, motivational feedback, self-efficacy, and knowledge transfer [31-34]. In order to enhance and strengthen previous research, a realist evaluation [35] was adopted to evaluate the final personalized self-management rehabilitation system (PSMrS) prototype in order to gain an insight into the value, usability, and potential impact on an individual's ability to self-manage their rehabilitation following a stroke [36].

The aim of this work was to understand the conditions under which technology-based rehabilitation would have an impact (outcome) on the motor behavior of the user—more specifically what would work for whom, in what context, and in what respect utilizing a realist evaluation framework [35]. This paper addresses this by focusing on the impact smart insole technology has on participants at home. The impacts are assessed by analyzing a participants' gait over time, which are then presented and discussed.

Futhermore, the rehabilitation system, its architecture, and technical components are presented along with the evaluation of the prototype with regards to the performance and usability of the system in the homes of stroke survivors.

Methods

Summary

The methodology was divided into 2 phases: the first was to design and develop a PSMrS for stroke survivors, and the second was to conduct a realist evaluation of the PSMrS involving stroke survivors (N=5) at home. Phase I was responsible for the design and development of a set of user requirements and to evolve the design through 3 development cycles. The realist evaluation took place in Phase II and quantitative results were obtained while the participants used the system at home. Table 1 provides an overview of participants' details; the mean age of participants was 57 years (range 42-73 years). Participants self-reported their computer experience as either none (+), fair (++), or a lot (+++). All of the participants routinely used a functional electrical stimulation (FES) device to enhance or stimulate dorsiflexion on their weaker side. While using this insole, none of the users used their FES at the same time. The FES and smart insole could not be used together simultaneously due to the added difficulty of donning and doffing the 2 devices on the lower limb. In addition, there was potential for interference of 1 system with the other.

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Table 1. Demographics of participants with stroke.

Participant ID	Age of participants with stroke/carer	Affected side	Time since stroke (months)	Computer experience	Walking aid (FES[a])
1	63/57	R hemi	13	++	None
2	73/73	L hemi	18	+	Frame or tripod
3	45/44	R hemi	18	+++	None
4	60/60	L hemi	15	++	None
5	42/44	R hemi	12	++	None

[a]FES: functional electrical stimulation.

Realist Evaluation

The realist evaluation [35] concerned aspects of the system that would facilitate behavior change associated with the self-management of rehabilitation. The evaluation systematically tested the context mechanism outcome configurations [37] by deploying the system in the homes of stroke survivors for a period of up to 7 weeks (Table 2).

Intervention

Participants (N=5) received training on how to use the system and had access to an electronic manual that contained instructional videos. Technical support was available via mobile phone from 9 am until 5 pm during weekdays. Each participant was asked to use the system as frequently and for as long as they desired for the duration of the intervention (N=5, mean=41 days, range 27-50). This allowed researchers to evaluate the variation in desired frequency and intensity of use. All of the participants received feedback following each walking activity. The interventions included both upper and lower limb exercises to promote a more comprehensive and holistic approach to the rehabilitation process.

Table 2. Two quantitative context mechanisms outcome configurations referred to as translating feedback and individual feedback for the personalized self-management rehabilitation system (PSMrS).

Feedback	Context	Mechanism	Outcome
Translating feedback	A system that translates biomechanical data through feedback.	The use of the PSMrS will facilitate the translation of biomechanical data which might enable the user to interpret their symptoms.	An understanding of symptoms and change in symptoms throughout the usage of the system. Measure: Qualitative data and quantitative Web-based data sources from insole.
Individual feedback	A system that provides individualized motivational feedback on the achievement of walking skill.	The use of the PSMrS might encourage increased intensity of practice with consequential neuroplastic changes.	Increased functioning and achievement of improved walking skill. Measure: Web-based quantitative data sources from insole.

Technology Deployed

The technology used to support the realist evaluation is presented in Figure 1 and consists of 3 parts. First, the touch screen interactive computing components, which are a home hub and mobile phone. The home hub facilitated the presentation, collection, forwarding, and synchronization of data and information related to the rehabilitation process. The upper limb intervention was only available through the home hub while the lower limb intervention was available on both the home hub and mobile phone components. Second, the mobile phone was combined with the smart insole to form a personal area network to enable gait information to be collected in real time and subsequently stored on the mobile phone. The home hub enabled participants to visualize their walking data via feedback screens (Multimedia Appendix 1) and make any adjustments via self-management. Third, upload of data to the server facilitated researchers to further analyze beyond those performed in real time for the participants.

These interventions were directly mapped onto 2 primary features offered by the PSMrS. The first intervention involved the monitoring and feedback of a participant's gait while performing walking activities. Walking activity was monitored by a smart insole that collected plantar foot pressure data, relating to a participant's gait. The smart insole is a product called Walkinsense produced by Kinematix, Portugal (formerly Tomorrow Options, Sheffield, United Kingdom). Information such as number of heel strikes for both affected and nonaffected sides, symmetry, and speed were calculated, stored, and fed back to participants. The second intervention focused on providing participants with access to a library of both upper and lower limb exercises, for example reaching, sit-to-stand, and stepping. A personalized selection of library exercises was created for each participant. This selection of exercises was mapped on to a predefined list of goals that participants could choose from. Instructional videos were presented to participants to promote clarity on form and precision of movement as these are deemed to be important factors in rehabilitation.

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The quality metrics chosen for feedback were the number of heel strikes and symmetry on the affected side. Feedback was provided through 2 screens, one for heel strikes and one for symmetry as presented in Multimedia Appendix 1.

Participants were given the opportunity to assess their personalized feedback and make appropriate changes where they deemed it necessary to do so, according to the principles of self-management.

Data Processing

The PSMrS uses a personal area network that comprises of a smart insole that transmits data in real time via a Bluetooth channel connected to a mobile phone for persistence. The smart insole, as presented in Figure 2, comprises a network of 8 force-sensitive resistors per foot or insole and samples data at a frequency of 100 Hz at a resolution of 8 bits. The data were captured in real time and uploaded to a server for further analysis for each walking activity.

Figure 1. Technology infrastructure used to support the realist evaluation consisted of touch screen interactive components: (1) a smart insole produced by Tomorrow Options, (2) used to collect gait information, and (3) a server used to analyze data.
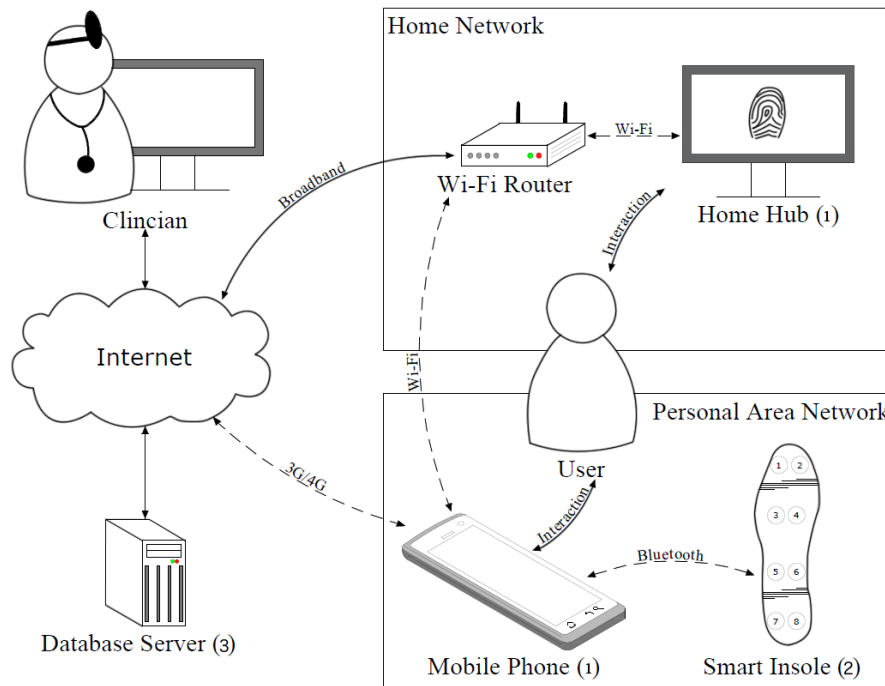
Figure 2. Walkinsense device. Top left: force sensitive resistors showing a typical layout configuration; bottom left: the size of a force sensitive resister in relation to a UK 5 pence piece; and right: attachment of devices to lower limb on a manikin.

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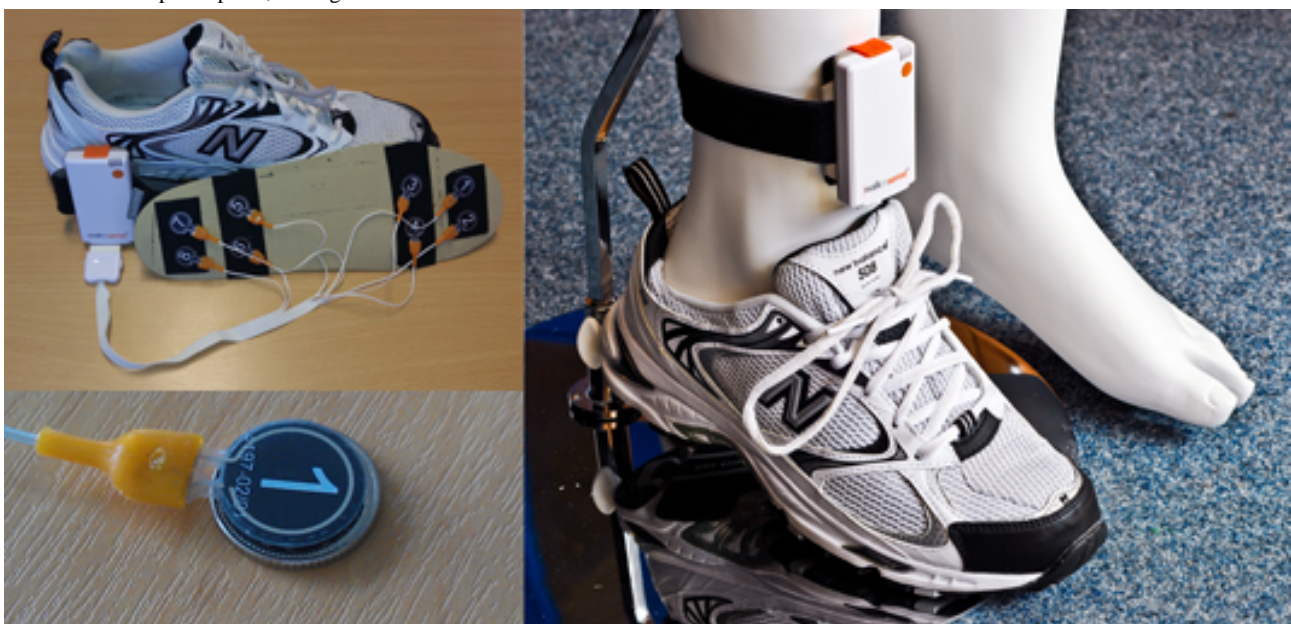
The time series data were analyzed to extract high-level information such as the length of the walking activity, number of steps, speed, number of heel strikes, and symmetry information. Once calculated, all of the metrics are persisted to a database table to be accessed for feedback to the stroke participant. A subsequent analysis was carried out across all of the participants to assess any trends, patterns of use, and to identify any strategies adopted.

Feature Extraction Algorithm

Time series data from 8 sensors were plotted for each insole allowing the data to be manually inspected and annotated to verify results (Figure 3). In order to process high-level features such as number of steps and symmetry, the lower level features had to be derived first. These features identify fundamental gait

events such as the point when the foot contacts and leaves the ground (Table 3).

The algorithm works by cycling through the time series data while detecting periods of pressure contact with the ground. These time periods are extracted to form a "step object" that is analyzed to produce the sublevel features listed in Table 3. The high-level features are calculated by analyzing all step objects produced for the whole walking activity. Over time, with significant reuse, sensors can potentially yield out of range values or become faulty. As part of the symmetry calculation, the algorithm takes into consideration any faulty sensors and removes them through a matching process with the opposite foot. This ensures that faulty sensors, should they occur, are not responsible for biasing or invalidating the symmetry calculation.

Figure 3. Time series data showing pressure distribution for a single foot strike.
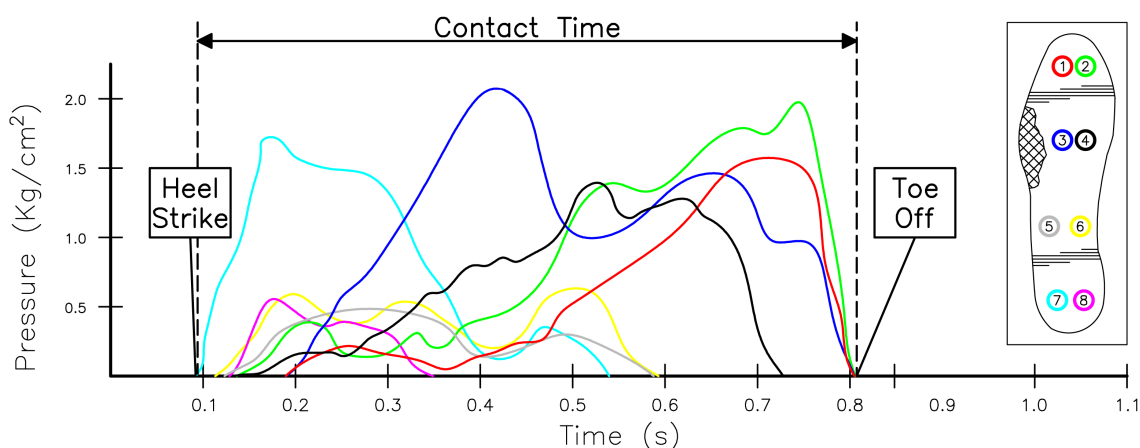
Table 3. Features and their description that were generated from the raw data collected from the insole.

Feature	Description	Units
Toe off	Time and sensor location when the foot leaves the ground	ms
Heel strike	Time and sensor location when the foot strikes the ground	ms
Contact time	Overall ground contact time of the foot	ms
Average pressure	Pressure exerted across the entire foot during contact time	kg/cm^2

Results

Summary

The results focus on the analysis of the quantitative data collected during the realist evaluation. From this, we assess if there were any significant improvements in performance in relation to walking activity and what area these improvements might relate to. The data were split into 2 halves: if a participant performed 20 walking activities throughout the entire realist evaluation, then the first 10 of these would constitute the first half and therefore represent baseline data. Rehabilitation markers were identified in relation to a participant's gait—these were number of heel strikes, symmetry, and speed. Heel strike

information was split into 2 parts to accommodate participant's affected versus nonaffected side.

The results across all 5 participants within the evaluation period demonstrated that on average, performance in relation to speed and heel strikes on a participant's affected side improved by 9.8% and 8.8%, respectively. In contrast, performance in heel strikes and symmetry on participant's nonaffected side decreased by 9.9% and 8.5%, respectively. Although these results were averaged across all the participants, this common pattern was evident (where participants' favored heel strikes on their affected side and increased speed) for 4 out of the 5 participants.

Participants were given feedback on 2 metrics: symmetry, and heel strikes on their affected side. The goals for these 2 metrics were personalized to 100% for heel strikes on their affected side and to 50% for symmetry. Although the participants' speed was not used as a feedback metric, information on this was collected. On average, across all 5 participants, speed of walking showed a marked increase of 9.8% during the evaluation period.

Figures 4-7 provide further insight into each of the metrics showing the change between the first and second halves of the realist evaluation. The symbols (square, circle, triangle, asterisk, and diamond) represent the average at the midpoint of the first and second half of the realist evaluation. A pattern has emerged for each of the 4 metrics: a marginal upward or leveling tendency for heel strikes on participant's affected side (Figure 4), a marginal decline for heel strikes on participants' nonaffected side (Figure 5), an upward or leveling tendency for speed (Figure 6), and a consistent decline for balance (with the exception of participant 5; Figure 7).

In addition, the analysis focused on participants' compliance, how often they used the system (Figure 9), and their intensity of use (length of walks; Figure 8). Together these metrics can be used to inform how participants were motivated throughout the realist evaluation and provide some indication in relation to participants' stamina and ability to recover.

Looking at the group of participants as a whole, it is probable that the pattern of use by participant 4 can be treated as an outlier. A closer analysis of participant 4 indicates that frequency of use declined from once per day to over once every 10 days. Coupling this pattern of infrequent use with a marked increase in the intensity of use (length of walks) from 90 seconds to 305 seconds could be an anomaly within the cohort profile. The remainder of the cohort, participants 1, 2, 3, and 5, has a similar pattern of use indicating both a slight decline in frequency and intensity of use. The rationale or explanation behind this can be linked to an adoption for new technologies for which there are many underlying reasons [38]. In particular, the novelty factor and how this could wear off during the first few times of use. Taking a closer look at these patterns of use does support this explanation as the first few times of use provide the marked increase necessary to create the slight decline viewed across participants 1, 2, 3, and 5.

The results from this paper focus on the quantitative data collected during the realist evaluation. Furthermore, information and details of qualitative results are published by Mawson [36]. Participant 2 described how the individual feedback scores helped to see progress towards recovery: "It makes me feel like I'm making progress. I'm going down that road to full recovery." When asked about achieving a lower score than a previous attempt, participant 4 suggested that this inspired them to try again: "It made me want to do it again to better it, yeah."
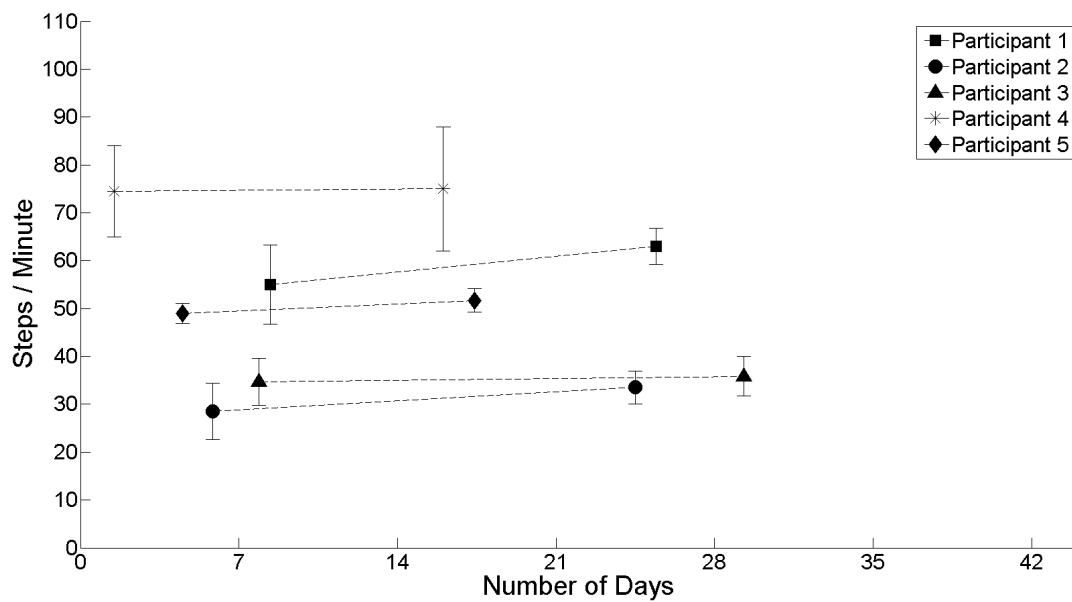
Figure 4. The average between the first and second half of the realist evaluation for heel strikes on the participants' affected side starting at day 1.
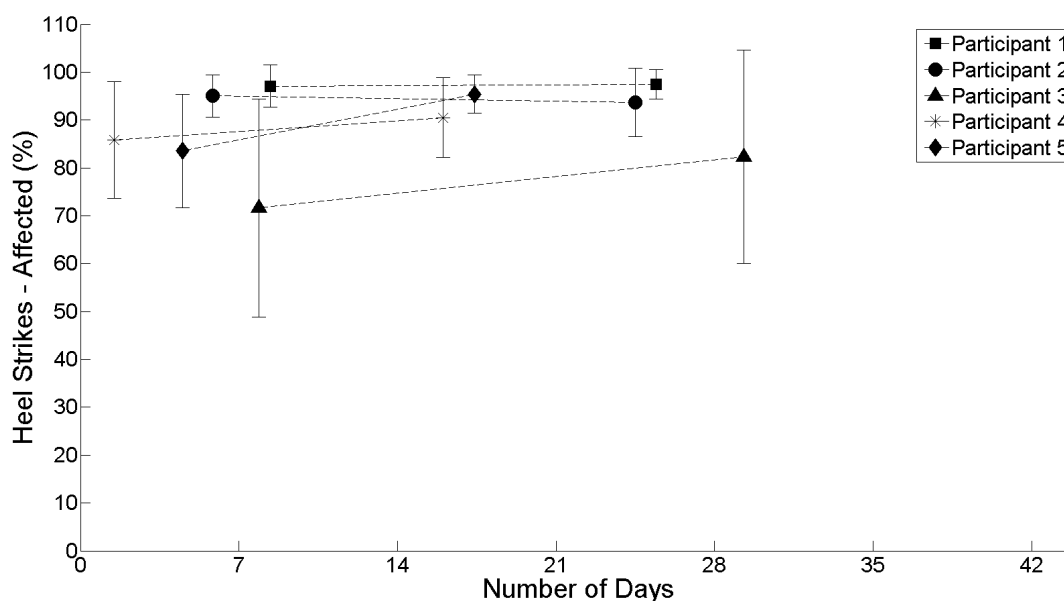
Figure 5. The average between the first and second half of the realist evaluation for heel strikes on the participants nonaffected side starting at day 1.
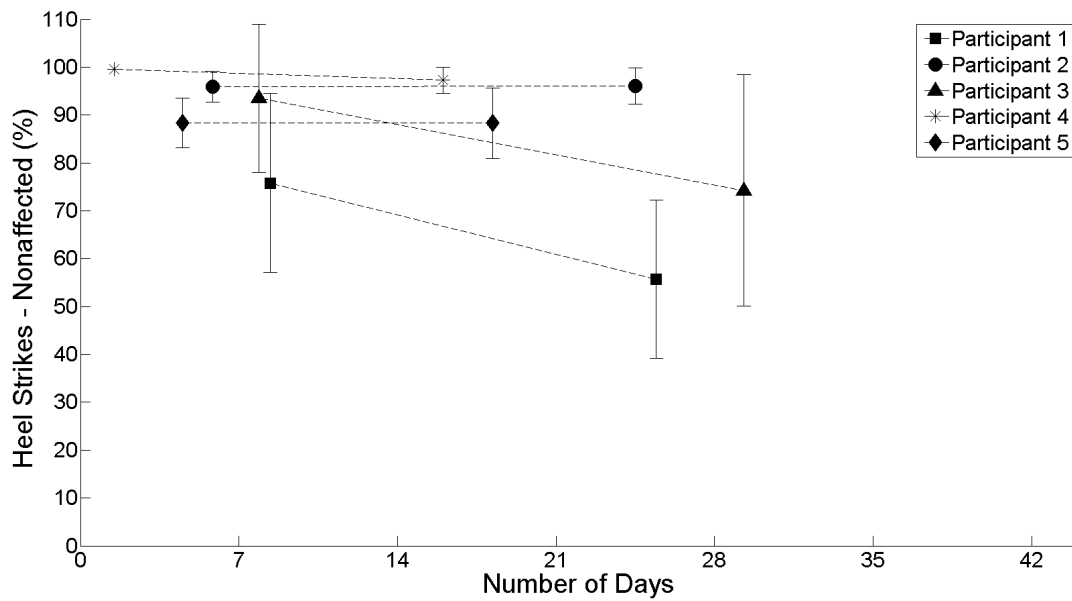

Figure 6. The average between the first and second half of the realist evaluation for steps/minute (speed) for all participants starting at day 1.

Figure 7. The average between the first and second half of the realist evaluation of symmetry for all participants starting at day 1.
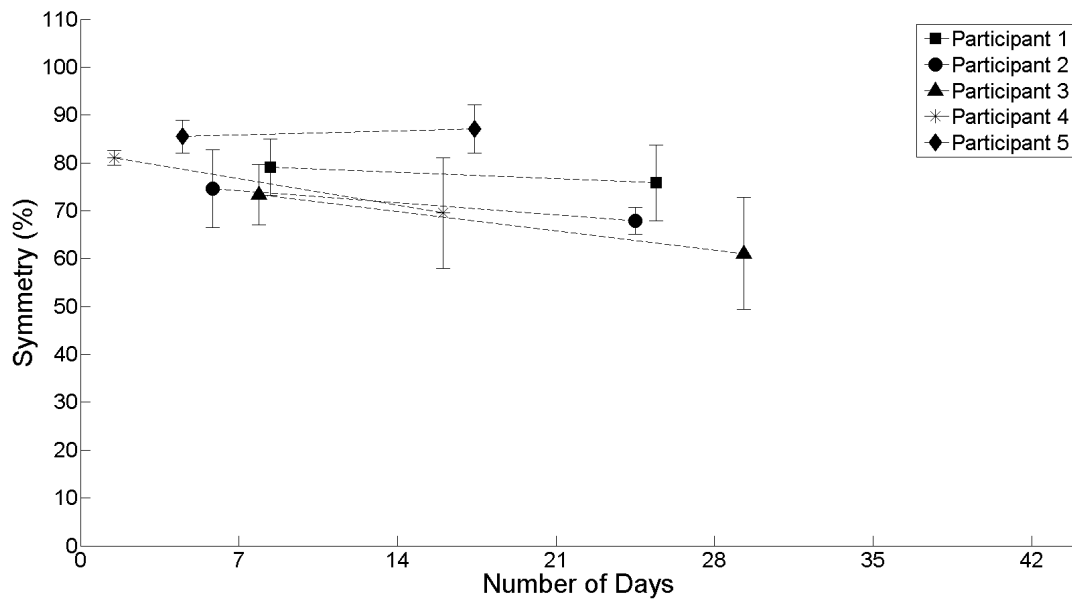
Figure 8. High level summary information in relation to the length of walk in seconds. With the exception of participant 4, it shows a very gradual decline in intensity of use.
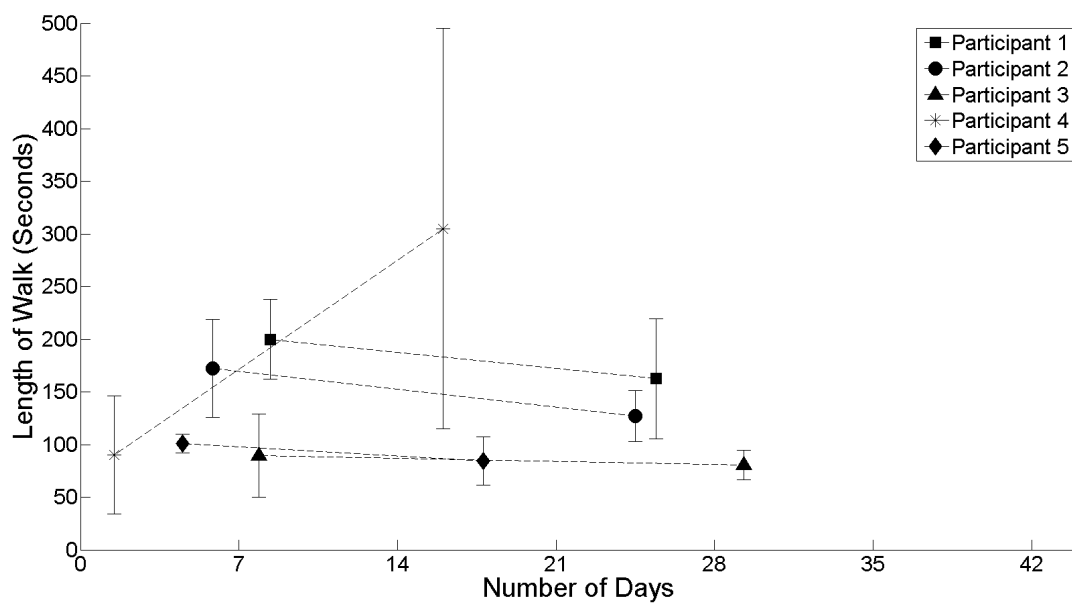
Figure 9. The frequency with which participants used the system irrespective of how intense that use was. This indicates an intention to perform a daily walk. It shows a decline in frequency of use from the first to second half of the realist evaluation.
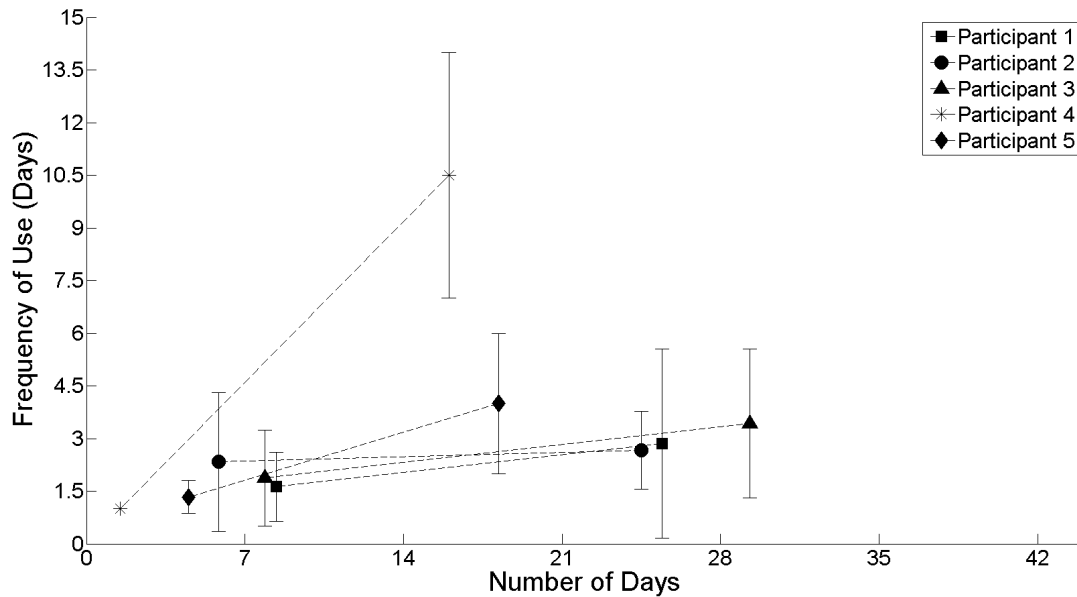
Discussion

Principal Findings

Although the results presented in this paper are not considered to be conclusive across a wider population of stroke participants, we have been able to add to existing literature by embedding our methods within an innovative realist evaluation methodology and by exploring changes in walking patterns within the real-world context of home-based rehabilitation. Although we have intervened by removing the FES, the results obtained can be clearly attributed to the technology being evaluated.

Theoretically, increased intensity together with motivational feedback should result in motor learning and neuroplastic adaptations. Nevertheless, the development of compensatory strategies has been documented in both rehabilitation literature [39-41] and in research findings [10,42]. As Kirker suggests, compensatory patterns are adaptive movements that reflect the central nervous system lesion, the structure of the motor system, and the environmental demands placed on the individual.

It seems a common strategy was adopted by 4 out of 5 participants to improve heel strikes on their affected side at the detriment of heel strikes on their nonaffected side. To achieve this strategy, participants compensated their balance by placing more weight and control on their nonaffected limb. Only participant 5 was able to improve heel striking on their affected limb while also improving their balance. Essentially this is a compensation strategy [41] whereby the nonaffected limb is used to compensate for balance and proper heel striking function to perform better on the rehabilitation feedback scores. This dual motor learning, compensation strategy previously described by Kirker et al [10] can be addressed with further research through the development of a new context mechanism outcome. Interestingly, all 5 participants increased their speed and for participants 1 and 2, this was relatively a significant increase of 23.8% and 17.5% respectfully. This increase in speed is

interesting for a number of reasons. Participants didn't receive any feedback on how they were performing in relation to speed, so the increase in speed is not related to any feedback or encouragement they would have received. Secondly, it seems counterintuitive to increase your speed to perform better at heel striking and balance yet all 5 participants did so. Speed is a metric that requires more research into its contribution and effects on the gait of stroke survivors at home.

A number of common patterns or strategies adopted in this study have been identified. It is clear that all participants compensated by not performing well on their good side to perform better on their affected side (for heel strikes). The results indicate that this compensation was almost a direct trade-off with an 8.8% increase versus a 9.9% decrease, respectively. In addition to this compensation strategy it is evident that participants' symmetry was also effected resulting in a proportionate decrease of 8.5%. This trade-off or dual strategy has been reported before [42] where it was shown that some stroke survivors improved functionally by using compensatory strategies, suggesting that factors predicting which participants use compensatory strategies needs further study. Whilst confirming and refining the original context mechanism outcomes, a further context mechanism outcome has therefore emerged from the evaluation linking the PSMrS directly to the dual strategy by increasing the demand on the individuals because of the increased intensity, goal planning, and the feedback screens (refer to Table 4).

Monitoring and providing feedback on key metrics related to improved quality of gait, aims to promote behavior change through goal setting, feedback, and self-management which map on to behavior change techniques [43]. In terms of behavior change, feedback scores had a significant effect as there was a focus toward achieving better results for heel strikes on their affected side versus their symmetry or heel strikes on their nonaffected side (Table 5). In addition, increasing speed may indicate a behavior change toward higher confidence levels

which can be confirmed by the qualitative research carried out by Mawson [36]. Furthermore, research should be conducted to confirm these assumptions as speed was not used as feedback.

The results indicate that the pattern of use in terms of frequency and intensity of use declined slightly from the first and second half of the realist evaluation. Future work would incorporate a mechanism to manage and maximize participant motivation by aligning mood and wellbeing feedback into overall feedback scores to avoid situations where participants become deflated. In addition, gamification elements could be added to provide enhanced motivation; these could take the form of levels or badges to accomplish milestones.

Table 4. Modified (translating feedback and individual feedback) and newly emerging context mechanism outcome (dual motor learning).

Description	Context	Mechanism	Outcome
Translating feedback	(Modified) A system that translates accurate, reliable quantitative biomechanical data through feedback.	The use of the PSMrS will facilitate the translation of biomechanical data which might enable the user to interpret their symptoms.	An understanding of symptoms and change in symptoms throughout the usage of the system. Measure: Qualitative data and quantitative Web-based data sources from insole.
Individual feedback	(Modified) A system that provides accurate, reliable quantitative individualized motivational feedback on the achievement of walking skill.	The use of the PSMrS might encourage increased intensity of practice with consequential neuroplastic changes.	Increased functioning and achievement of improved walking skill. Measure: Web-based quantitative data sources from insole.
Dual motor learning	(New) A system that increases environmental demands on the individual.	(New) The use of the PSMrS might encourage functional recovery achieved through dual motor learning and compensatory strategies.	(New) Increased walking skill with an increase in compensatory strategies. Dual strategy adopted. Measure: Web-based quantitative data sources from insole.

Table 5. Performance for all 5 participants indicates relative and contrasting scores for heel strikes on both sides, balance, and speed. The relative scores are obtained by contrasting the first and second half usage during the realist evaluation.

Participant ID	Heel strikes (Affected)	Heel strikes (Nonaffected)	Balance (Affected)	Speed
1	+0.7%	−32.3%	−7.4%	+23.8%
2	−1.4%	+0.1%	−9.1%	+17.5%
3	+29.0%	−11.5%	−15.8%	+1.5%
4	+5.4%	−2.3%	−14.2%	+0.7%
5	+10.5%	−3.7%	+4.0%	+5.5%

Limitations

The first limitation is the lack of a nonintervention baseline data to compare and contrast against the realist evaluation. The study is therefore limited to comparing and contrasting data within the first and second halves of the realist evaluation. The second limitation relates to both the number of participants and duration of the study which could be extended to establish significance to the results. Future work aims to address this by evaluating this approach and technology through a randomized controlled trial.

Conclusions

This research aimed to gain a deeper insight into the impact of innovative technologies under the context of home-based rehabilitation for stroke survivors. In this study, the authors present the results from a realist evaluation that focuses on the introduction of smart insole technology to a cohort of (N=5) stroke participants. The study focuses on the quantitative data obtained and analyzed from walking activity data generated over a 2-month period in participants' homes using realist evaluation methodology. The results have provided further insight into how stroke participants perform during walking activities at home without direct instruction and supervision. The results show that participants may be willing to compensate and sacrifice performance in symmetry or balance in favor of heel strikes on their affected side. Speed was also identified as a metric that exhibited a marked increase through higher confident levels after using the smart insole technology for a short period of time which was an unexpected result. Motivational aspects of the system should also be improved to encourage higher levels of frequency and intensity of use.

Acknowledgments

Conflicts of Interest

None declared.

Multimedia Appendix 1

Symmetry or balance feedback screen (top), Heel strikes feedback screen (bottom).

[PNG File, 989KB - rehab_v3i2e11_app1.png]

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Review

Validated Smartphone-Based Apps for Ear and Hearing Assessments: A Review

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Abstract

Background: An estimated 360 million people have a disabling hearing impairment globally, the vast majority of whom live in low- and middle-income countries (LMICs). Early identification through screening is important to negate the negative effects of untreated hearing impairment. Substantial barriers exist in screening for hearing impairment in LMICs, such as the requirement for skilled hearing health care professionals and prohibitively expensive specialist equipment to measure hearing. These challenges may be overcome through utilization of increasingly available smartphone app technologies for ear and hearing assessments that are easy to use by unskilled professionals.

Objective: Our objective was to identify and compare available apps for ear and hearing assessments and consider the incorporation of such apps into hearing screening programs

Methods: In July 2015, the commercial app stores Google Play and Apple App Store were searched to identify apps for ear and hearing assessments. Thereafter, six databases (EMBASE, MEDLINE, Global Health, Web of Science, CINAHL, and mHealth Evidence) were searched to assess which of the apps identified in the commercial review had been validated against gold standard measures. A comparison was made between validated apps.

Results: App store search queries returned 30 apps that could be used for ear and hearing assessments, the majority of which are for performing audiometry. The literature search identified 11 eligible validity studies that examined 6 different apps. uHear, an app for self-administered audiometry, was validated in the highest number of peer reviewed studies against gold standard pure tone audiometry (n=5). However, the accuracy of uHear varied across these studies.

Conclusions: Very few of the available apps have been validated in peer-reviewed studies. Of the apps that have been validated, further independent research is required to fully understand their accuracy at detecting ear and hearing conditions.

Introduction

In 2012, the World Health Organization (WHO) estimated that disabling hearing impairment (DHI) affects approximately 360 million people, or 5.3% of the global population [1,2]. The definition of DHI is a pure tone average (PTAv) of thresholds at 500, 1000, 2000 and 4000 hertz (Hz) in the better hearing ear of greater than 30 decibels (dB) in children, and greater than 40 dB in adults. Most people with DHI live in low- and middle-income countries (LMICs), with the greatest burden in the Asian Pacific, southern Asian, and sub-Saharan African regions [3]. The estimated global prevalence of DHI is increasing [3,4], and may be due to greater life expectancy in many countries, resulting in: increased prevalence of age-related hearing loss; early detection of hearing loss facilitated through increased availability of hearing screening equipment; increasing hearing loss due to occupational, recreational, and environmental noise exposure; and increased and extensive use of ototoxic

medications for treating a range of medical conditions, such as human immunodeficiency virus (HIV) [3,4].

Hearing loss has a substantial impact on psychosocial wellbeing and economic independence [3]. If acquired in childhood, before speech has developed, hearing loss can impede language development and hence limit educational attainment [3]. Hearing loss also has high societal costs, mainly due to losses in productivity [5]. If hearing impairment is identified early and treatment is provided, many of these negative effects can be avoided [6,7]. Screening for hearing impairment can be useful for a range of age groups and patient groups, including newborns, to detect congenital hearing impairment; school children, to detect late-onset hearing impairment; the elderly, to identify age-related hearing loss (presbyacusis); and those with HIV [3,8-11]. In addition, screening for hearing impairment in population-based surveys is important to determine its magnitude and plan services accordingly [12]. However, substantial challenges exist in screening for hearing impairment (especially in LMICs) such as the need for a quiet testing environment, prohibitively expensive specialist hearing assessment equipment that requires regular calibration, and skilled professionals to conduct clinical tests. In many LMICs, there is a severe shortage of hearing health care professionals (ie, audiologists, speech pathologists, and ear, nose, and throat [ENT] specialists). In most of sub-Saharan Africa, services are either nonexistent or limited to urban centers, resulting in 1 ENT per 250,000 to 7.1 million people [13]. This scarcity contrasts with Europe, where there is 1 ENT per 10,000-30,000 people [14]. Due to these barriers, hearing impairment remains undetected and unmanaged for a substantial number of people in LMICs, and robust data from population-based surveys is lacking. 2012 WHO prevalence estimates comprised of 42 population-based surveys in 29 countries [1,2,6]. In contrast, the Rapid Assessment of Avoidable Blindness survey methodology been used in over 200 population-based surveys of visual impairment [33].

The gold standard for hearing screening for people >4 years of age is Pure Tone Audiometry (PTA) [12]. For subjects <4 years of age, objective tests such as Otoacoustic Emissions (OAE) and Auditory Brainstem Response (ABR) testing are recommended [12]. Understanding the probable causes of hearing loss is vital for management and referral processes. Causes of hearing loss are typically determined using a comprehensive battery of tests. In hearing screening programs, these tests include tympanometry (a test of middle ear function) and otoscopy (visual examination of the eardrum). The equipment and expertise required for these tests and examinations is lacking. However, new and innovative technologies that are low-cost, easy to use, and automated have recently been developed and may be useful in overcoming some of the challenges. For instance, replacing PTA (typically conducted by an audiologist) with automated computer-based audiometry can provide comparable results on threshold testing [15]. Developers of smartphone apps have begun to harness this technology to generate apps for performing self-administered hearing screening tests. In addition, apps exist for performing video otoscopy, whereby images of the eardrum are captured and may be sent to an ENT specialist to diagnose and manage ear conditions remotely. With the global rise in smartphone penetration, apps offer a promising avenue to screen for hearing impairment and assess the causes in a low-cost manner. A large number of apps for measuring ear and hearing function are thought to exist that can potentially be utilized, but their scientific validity has not been reviewed in-depth. The aim of this review is to identify available apps to screen for hearing impairment, and compare the features and peer-reviewed validation studies performed to date.

Methods

A search was conducted to find apps for ear and hearing assessments, using the most popular commercial app stores by market share: Google Play (Android apps) and the Apple App Store (iPhone/iPad apps) [16]. Next, a review of peer-reviewed literature was conducted to determine whether any of the identified apps had been validated against gold standard measures.

Google Play and Apple App Store Search

A search was conducted on Google Play and Apple App Store in July 2015. The main types of apps searched were those that could perform audiometry, tympanometry, OAEs, ABR testing, and otoscopy. These tests were chosen, as they can be used for assessment of ear and hearing function in a range of settings, including screening programs and population-based surveys [12]. A range of search terms were used, including clinically-recognized terms such as *audiometry* and layman's terms such as *hearing test*. Table 1 provides a list of all search terms used.

Table 1. Search terms used in Google Play and Apple App Store.

Concept	Search terms used
Audiometry	audiogram
	audiology
	audiometry
	hearing exam
	hearing check
	hearing loss
	hearing problem
	hearing
	hearing test
	hear
	pure tone audiometry
Tympanometry	tympanometry
	ear
	ear nose and throat
	ENT
	ear test
	otolaryngology
	middle ear
	middle ear test
Otoacoustic Emissions	otoacoustic emissions
	OAE
	ABR
Otoscopy	otoscope
	otoscopy
	otorhinoendoscope
	otolaryngoscope

Inclusion and Exclusion Criteria

App titles were initially screened for relevance to the measurement of auditory function or ear examination. Apps were excluded based on their title if it was clear that the app was not applicable. For example, in a search of *hearing test,* apps such as *Phone*, *Dog Hearing Test,* and *Motorola Gallery* were excluded based on title. Those with relevant (eg, *Hearing Test*) or ambiguous titles (eg, *iCare Health Monitor*) went through a second screening, in which they were reviewed in more detail using the descriptions in the app store and on the app's website. Apps were included if they were self-administered or professionally administered tests of ear or hearing function. Apps were excluded if they did not focus on ear examination or audiological testing; they were not in English; they were included in the category of games, entertainment, or music; or they were intended for educational purposes.

Literature Review of Smartphone Apps

Information Sources

Once the app store review was complete, a literature review was conducted in July 2015 to assess app validity testing. 6 databases were searched for peer-reviewed studies related to apps of ear and hearing function: PubMed/MEDLINE, EMBASE, Global Health, Web of Science, CINHAL, and mHealth Evidence. Comprehensive search terms for smartphone apps and auditory function were identified through MeSH and previous systematic reviews on similar topics. The names of identified apps from the commercial review were also included (see Multimedia Appendix 1). Developers of apps that were validated in peer-reviewed literature were contacted if specific information about the app was not available online.

Study Eligibility Criteria

Articles published between June 2007 and July 2015 were included in the search to align with the time-period during which apps have been available [17]. Any primary study identified in

the app stores' review that compared an app to gold standard methods was considered for inclusion. Studies that measured outcomes that allowed judgement of the app's performance were included. These outcomes included: sensitivity, specificity, negative and positive predictive values, difference in pure-tone thresholds, and kappa diagnostic agreement. No restrictions were placed on study location, or types of participants included in the studies. Studies were excluded if they were not in the English language, or the study was not peer-reviewed. This review focused on the validity of apps available for download from commercial app stores. If the article did not specify the name of the app, or if the app being studied was not previously identified in the app stores' review, the author was contacted for further information about the app and its availability. The article was included if the author could provide the app's name and the app was available for purchase, either on Google Play, the Apple App Store, or elsewhere.

Study Selection

Articles were screened by two reviewers (TB and DP) first by titles, then abstract, and finally by full paper to determine eligibility.

Data Extraction

Data was extracted from eligible studies for the following study components:

1. *Methods*, including study design, comparison being made (ie, index test [app] and reference test [gold standard]), single or multiple smartphone devices used, headphone/transducer type, calibration methods, and test frequencies.

2. *Participants*, including age, sex, and sample size.

3. *Study location*, including country and setting.

4. *Publication details*, including year, journal, and declaration of conflicts of interest.

5. *Outcomes*, including type of outcome, definitions (eg, definition of hearing loss).

6. *Results*, including relevant measure of validity.

All data was extracted by one reviewer (TB), and checked by the second reviewer (DP) to ensure accuracy.

Methodological Quality of Studies

Methodological quality for each study was assessed using the Quality Assessment for Diagnostic Accuracy Studies (QUADAS-2) tool [18,19]. This tool assesses the following 4 domains:

1. *Patient selection*: assessment of study design, sampling method, and selection criteria.

2. *Index test (app)*: assessment of chosen test (app), testing method, and interpretation.

3. *Reference standard*: assessment of choice of reference standard and interpretation.

4. *Flow and timing*: assessment of time interval between index and reference tests, proportion of sample receiving reference standard, and proportion of participants included in the analysis.

Each domain was assessed in terms of risk of bias, and the first three domains were assessed in terms of concerns regarding applicability to the review question. Risk of bias and concerns regarding applicability were scored as *low*, *high*, or *unclear* using a series of signalling questions. If each signaling question had an answer of, "yes," the domain was rated as having a low risk of bias or low concern of applicability. If any signaling question was answered, "no," the domain was scored as high risk of bias or high concern of applicability. If any domain provided inadequate information to make a judgement, the domain was scored as, "unclear." Each paper was reviewed independently for quality by two reviewers (TB and DP).

Synthesis of Results

Results from the literature review were synthesized using a narrative approach, rather than a meta-analysis, due to the heterogeneity of included studies.

## Results

Google Play and Apple App Store Review

Over 1000 apps were reviewed in the searches of Google Play and the Apple App Store, 30 of which met the inclusion criteria (Figure 1). Of these, 17% (5/30) were Android (Google) apps, 70% (21/30) were iOS (Apple) apps, and a further 13% (4/30) were compatible with both Android and iOS. Considering the function of the apps, audiometry apps formed the majority, with 26 of the 30 (87%) functioning as either self-administered automated PTA or professionally administered PTA. The remaining apps (4/30, 13%) were designed for performing otoscopy and required a separate specula phone attachment. No apps for tympanometry, OAEs, or ABR were identified. Details of the identified apps can be found in Multimedia Appendix 2.

### Literature Review of Smartphone Apps

Search Results

The literature review yielded 534 results: 182 in EMBASE, 157 in MEDLINE, 153 in Web of Science, 21 in CINAHL, 13 in Global Health, and 8 in mHealth Evidence. After removing duplicates across search engines, and screening titles and abstracts for relevant articles, 22 studies remained. Full text article screening resulted in 7 eligible studies. Three studies were excluded, as the app under study was not specified. Attempts were made to contact the authors of these papers for further information; however, this was not successful. Four additional studies were identified from reference lists of included articles, resulting in the inclusion of 11 studies overall (Figure 2). One further article was identified through app website review; however, the full text could not be located and therefore this article was excluded.

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Figure 1. Flow diagram for apps found in app stores. Numbers are approximate due to limitations with the search platform (a=exact number of hits not provided and thus manual counting conducted).
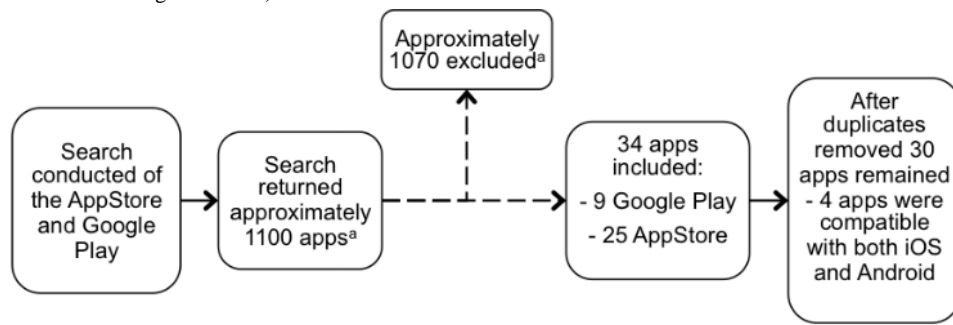
Figure 2. Flowchart of study selection process.
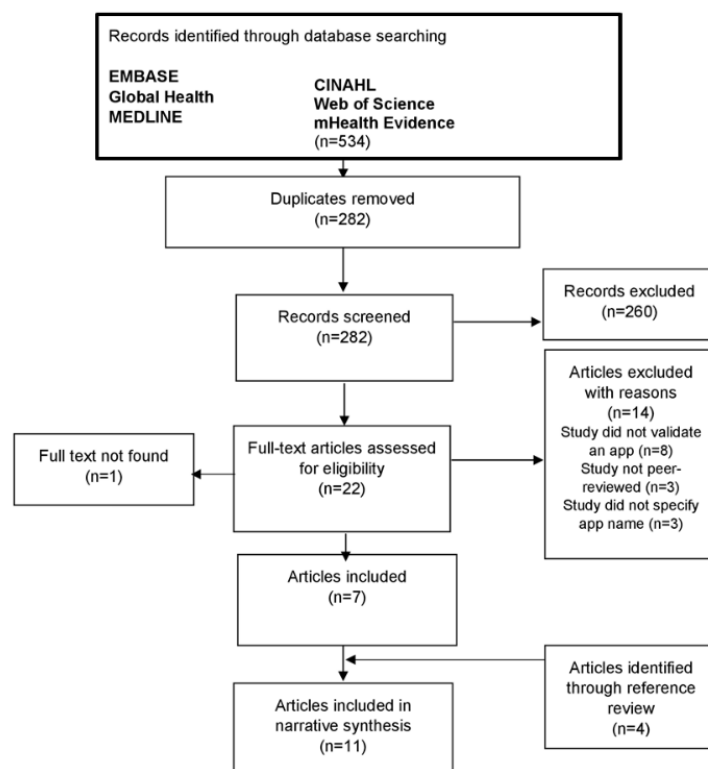
Table 2. Characteristics of apps validated in peer-reviewed literature.

App and operating system	App function	Cost (US $)[a]	Test frequency (kilohertz)	Maximum testing output (decibels)	Calibration	Transducer type and model	Additional features
uHear, iOS	Self-administered audiometry app	Free[b]	0.25, 0.5, 1, 2, 4, 6	90	Calibrated with standard Apple headphones using reference equivalent threshold sound pressure levels for TDH39 headphones (ISO389-1)	Air conduction (AC), standard apple headphones; bone conduction (BC), not measured	Noise monitoring, data storage with user identification, and questionnaire to evaluate the impact of hearing loss
shoeBOX audiometry, iOS	Self- or tester-administered audiometry app	Humanitarian $2000[c], standard version $3100[c], professional version $4100[c]	0.25, 0.5, 1, 2, 4, 6, 8	90-115	Calibrated with audiometric transducers using American National Standards Institute S3.6-2004 standards	AC, TDH-39 or EAR 3A insert headphones; BC, B-71 bone transducer	Noise monitoring, masking (auto calculated), and data management (cloud)
AudCal, iOS	Tester-administered audiometry app	$1.99[b]	0.5, 1, 2, 3, 4, 8	75	Calibrated for most models of iPhone/iPad using Apple headphones (standards not specified)	AC, Apple headphones; BC, not measured	Ability to export results as a photograph to photos app, and integrated with Print, Mail, and WhatsApp
hearScreen, Android	Tester-administered screening audiometry app (ie, pass/fail result)	$600[d]	1, 2, 4	40	Calibrated with nonaudiometric headphones according to ISO389-1-specified standards (within 0.1 decibel accuracy)	AC, Sennheiser HD202 headphones; BC, not measured	Noise monitoring, data capturing and sharing, and location-based referral
EarTrumpet, iOS	Self-administered audiometry app	$3.99[b]	0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4, 6, 8	90-100	Calibrated with Apple's earbuds (standards not specified)	AC, commercially available earbuds (eg, standard Apple headphones); BC, not measured	Data storage, automated masking noise, and amplification device
CellScope, iOS	Otoscopy app with separate attachment	$79[e] for iPhone case, otoscope attachment, 4 reusable specula	Not applicable (N/A)	N/A	N/A	N/A	Port for pneumatic otoscopy

[a]Subject to change.

[b]Price excludes cost of device and transducers.

[c]Price includes transducers, software, and first year's calibration. Price excludes the price of the iPad.

[d]Price includes device, transducers, and calibration.

[e]Price excludes cost of device.

Results of Included Studies

Of the 30 apps found in the review of the app stores, 5 appeared in validation studies in the peer-reviewed literature. These apps were uHear, shoeBOX audiometry, EarTrumpet, CellScope, and AudCal. One study was identified in the literature that validated an Android hearing screening app, hearScreen, that is not yet commercially available on Google Play. Thus, 6 previously validated apps were identified in the review. Of these apps, the function of 4 was self- or tester-administered PTA (uHear, shoeBOX audiometry, AudCal, and EarTrumpet), one performed screening audiometry (hearScreen; pass/fail result), and one functioned as video otoscope (CellScope).

Table 2 provides a summary of the validated apps and their specific characteristics, including function, costs, test frequencies, maximum output, calibration method, recommended transducers, and administration method.

Overview of Study Characteristics

The 11 selected studies are summarized in Multimedia Appendix 3 by study setting, study design, participants/sample and sample size, index (app) and reference test (gold standard), transducers and devices used, test administration method (eg, self- or tester-administered), outcome measures, calibration method, and results. Studies were performed in Canada (n=3) [20-22], Spain (n=1) [23], Israel (n=2) [24,25], USA (n=2) [26,27], and South Africa (n=3) [28-30]. The sample size of the included studies ranged from 25 to 110 participants. Participants in the

included studies came from a range of age groups: adults (>18 years; n=4) [21,23,24,27], the elderly (>65 years; n=1) [25], children (<18 years; n=5) [20,26,28,30], and both children and adults (15-80 years; n=1) [29].

All included studies used a within-subjects' study design. Ten of the 11 studies focused on comparing audiometry apps to conventional PTA [20-25,27-30], while the remaining study compared the diagnosis made with an otoscope app to traditional otoscopy [26].

Of the 10 studies validating audiometry apps, the majority carried out testing with the app in a quiet room (ambient noise levels 40-50 A-weighted decibels [dBA]; n=7) [21,24,25,27-30]. The remaining studies were performed only in a soundproof room (ambient noise <40 dBA; n=3) [20,22,23]. Three studies performed testing in multiple environments to determine the effect of ambient noise on test accuracy [21,27,29]. In terms of outcome measures, most studies (6/10, 60%) performed sensitivity and specificity analyses with defined pass/fail dB cut-offs [20-22,24,25,29]. The remaining studies (4/10, 40%) used alternative outcome measures, including the mean difference in thresholds between the app and conventional PTA [23,27,28,30]. Validation of audiometry apps in all 10 studies focused on the comparison of air conduction (AC) thresholds only, as opposed to including bone conduction (BC) threshold as well. In the single study validating the otoscopy app, Cohen's kappa agreement was used to determine diagnostic agreement with traditional otoscopy [26].

Summary of Main Results

Audiometry Apps

Of all the apps reviewed in the literature, uHear has been validated in the most studies, none of which declared a conflict of interest (n=5). Results from 3 of the 5 studies on uHear suggest that when screening for moderate or worse DHI (PTAv >40 decibels Hearing Level [dBHL]) in adults, a high sensitivity (ranging from 98.2-100%) was achieved; however, specificity was variable (ranging from 60.0-82.1%) if tests were conducted in environments with ambient noise floor at 40-50 dBA (quiet room) [21,25,29]. Ambient noise levels had significant impacts on the accuracy of uHear [21,29]. Sensitivity remained high in all test settings; however, specificity decreased in a waiting room setting (ambient noise >50 dBA) and increased when conducted in a soundproof room (ambient noise <40 dBA) [29]. Two studies concluded that uHear cannot accurately determine the precise level of hearing impairment as compared to conventional PTA, suggesting that the app could be used for screening, but not diagnostic purposes [21,25].

Two validity studies compared shoeBOX audiometry to standard pediatric audiometry, both of which declared a conflict of interest [20,22]. Sensitivity in these studies ranged from 91.2-93.3% and specificity ranged from 57.8-94.5%, depending on transducers used and test environment [20]. Individual validity studies were identified for EarTrumpet, AudCal, and hearScreen, each declaring a conflict of interest. Hearing thresholds obtained with EarTrumpet and AudCal were found to be within 10 dBHL of conventional PTA, on average [23,27]. hearScreen, a screening app that gives a pass/refer result, was found to have comparable referral rates to conventional screening audiometry [30].

Otoscopy Apps

Only one study focused on validating an otoscopy app. This study compared the diagnosis obtained using traditional otoscopy to that obtained using the iPhone otoscope, CellScope (n=54) [26]. This study found high levels of agreement between the two diagnostic methods. Refer to Multimedia Appendix 3 for further details of the study results.

Table 3. Summary of quality review of included studies (assessed using the QUADAS-2 tool) where 1 represents low risk of bias/low concern of applicability, 2 represents unclear/inadequate information to make judgement, and 3 represents high risk of bias/high concern of applicability.

Study authors (year)	Risk of bias				Applicability concerns		
	Patient Selection	Index Test	Reference Standard	Flow and Timing	Patient Selection	Index Test	Reference Standard
Abu-Ghanem et al (2015) [25]	3	1	1	1	3	1	1
Khoza-Shangase et al (2013) [28]	3	1	1	1	1	1	1
Peer et al (2015) [29]	1	1	1	3	1	1	1
Szudek et al (2012) [21]	2	1	1	1	1	1	1
Handzel et al (2013) [24]	3	3	1	1	3	3	3
Foulad et al (2013) [27]	1	1	1	1	1	1	1
Yeung et al (2013) [20]	1	1	1	3	1	1	1
Yeung et al (2015) [22]	1	3	1	3	1	1	1
Larrosa et al (2015) [23]	1	1	1	1	1	1	1
Swanepoel et al (2014) [30]	3	1	1	1	1	1	1
Richards et al (2015) [26]	3	3	1	1	1	1	1

Methodological Quality of Included Studies

Of the 11 peer-reviewed studies included in this review, 2 achieved a rating of *low risk of bias* and *low concern of applicability* in all domains [23,27]. The main source of bias in the included studies was selection bias. Results of the quality assessment are summarized in Table 3 and detailed in Multimedia Appendix 4.

Discussion

Screening for hearing impairment is not feasible for many LMICs, mainly due to the dearth of skilled professionals available to conduct the required tests and high costs of specialist equipment. However, the increasing availability of apps provides an opportunity to integrate their use into screening for ear and hearing conditions in a cost effective and mobile way. This paper provides a comprehensive summary of the currently available apps for ear and hearing assessments (up to July 2015) and provides a summary of those that have been validated against gold standard measures.

Thirty commercially available apps meeting the inclusion criteria were identified on Google Play and the Apple App Store. Of these, only 5 had undergone validation, as per the peer-reviewed literature (Table 2). One additional peer-reviewed validation study referred to an Android app that is not yet available commercially. The vast majority of apps identified in the initial commercial review have not been validated against a gold standard measure in peer-reviewed literature. Most of the available apps were designed to perform audiometry (26/30, 87%) with a small proportion for otoscopy (4/30, 13%). No apps were identified for conducting OAEs, ABR, or tympanometry.

The literature review identified 11 peer-reviewed validation studies. Studies were quite heterogeneous, with variation in the cut-off level for performing sensitivity/specificity analyses, patient population, units of analysis (results of each ear separately or individual), and exclusion/inclusion criteria for participants, thus making direct comparisons across apps difficult. The quality of included studies was variable, with only 2 studies achieving a *low risk of bias* and *low concerns about applicability* in all domains (Table 3). Five peer reviewed studies were identified on uHear; however, the accuracy results varied considerably across these studies (Multimedia Appendix 3) [21,24,25,28,29]. A specificity as low as 60%, found by Abu-Ghanem et al in a quiet room setting, would result in a high rate of false positives in a screening program, and thus an unnecessary rate of referrals for diagnostic assessments, which would increase the burden on already strained health services [25]. The small sample sizes and the limited variability in degree and types of hearing loss included in the studies on uHear may limit generalizability based on the studies reviewed. Individual peer-reviewed validation studies were identified for AudCal, hearScreen, EarTrumpet, and CellScope [23,27,30]. Although the results of these studies appear to be promising, there is limited evidence to allow robust conclusions to be drawn.

Several studies demonstrated that the testing environment had a significant impact on the accuracy of results [21,27,29]. This

finding is important, as ambient noise levels in screening environments are a substantial challenge and can often exceed the recommended minimum of 40 dBA [7]. Studies of audiometry apps focused on comparison with AC thresholds only, reinforcing the fact that these apps function as screening (rather than diagnostic) tools. BC testing is important for differentiating between conductive and sensorineural hearing loss; however, shoeBOX audiometry that runs on an iPad device is currently the only app compatible with BC transducers. Thus, the validity of BC testing from smartphone devices warrants further investigation. The range of frequencies that are tested in the current audiometry apps does not typically extend to 8000 Hz, thus screening for certain conditions such as ototoxicity and noise-induced hearing loss would not be possible with current app technology.

Most studies conducted tests using a single device and transducer; however, in reality there may be significant variability in results obtained with different transducer/device combinations due to issues with calibration. Annual calibration of audiometric devices is a key consideration to ensure test accuracy. Of 10 audiometry studies, only half performed calibration as part of their study [20,22,23,27,30]. This finding may be due to the fact that no standardized calibration procedure currently exists for performing tests on smartphone devices coupled with nonaudiometric headphones [30]. Several recent studies have investigated calibration methods; however, further research evidence is necessary [31,32]. Some authors suggested that poor sound attenuation provided by commercially available earbuds might have resulted in the poor accuracy of results found in nonsoundproof environments. Accuracy may improve if headphones with greater attenuation of ambient noise are utilized. However, the cost of these types of headphones can be prohibitive and calibration is still an important issue. Audiometric headphones adhering to International Organization for Standardization calibration standards (ISO389-9:2009) are vastly more expensive than commercially available headphones. Nonaudiometric supraaural headphones may assist in providing some attenuation from ambient noise. Swanepoel et al determined that Sennheiser HD202 headphones coupled to a smartphone hearing screening device can be calibrated to a professional standard using TDH-39 Reference Equivalent Threshold in Sound Pressure Levels as a reference [30]. Thus, it seems possible to use lower-cost transducers whilst ensuring test accuracy. The expertise required to professionally calibrate audiometric devices is often nonexistent in low resource settings, and equipment can remain out of calibration for lengthy periods. Hence, ongoing calibration is an additional challenge for performing accurate screening of hearing loss using apps.

Although the cost of the apps themselves are low (indeed many are free; Multimedia Appendix 2) additional costs are incurred for the device, headphones, and regular calibration. Android devices are often much less expensive than Apple products and more widely available in LMICs; however, the vast majority of available apps identified in this review were designed for Apple devices. Some of the apps identified in the literature search (shoeBOX audiometry, and hearScreen) are sold as a package including headphones, calibration for the first year, and the device (hearScreen). Although these apps appear to be

higher-cost, these features allow for a level of quality control that is not currently available for apps that can be downloaded from app stores and used on various device/transducer combinations.

Strengths and Limitations

This review has several strengths. Comprehensive search terms were identified and applied across multiple electronic databases to reduce publication bias. A clear approach to searching, screening, reviewing, and extracting data was performed independently by two reviewers. Citation bias was minimized by reviewing references of included studies. Thus, the search strategy of peer-reviewed literature is not likely to be a significant limitation.

The search of app stores was conducted using a range of search terms and the most commonly used commercial app stores were searched; however, this search had several limitations. First, unlike searches of academic databases, app store searches do not allow complex search functions such as Boolean operators or the searching of phrases such as, "hearing test." Second, search engines did not provide the total number of hits for each search. Therefore, an estimation had to be made of the total number of apps reviewed (>1000). In addition, app store categories may not always reflect the true nature of the app, implying that some relevant apps (ie, those in the category of games) may have been missed. Furthermore, the range of search terms used may not have been fully exhaustive. For instance, alternative screening tools for hearing loss, such as self-reported questionnaires, were not included in the search. Finally, if time and resources permitted, each app would have been downloaded and tested to assess eligibility. However, this was not feasible within the scope of this study. Thus, assessment of the apps' eligibility proved difficult in some instances if limited or vague information about the app was provided on the app stores. Given these limitations, the search of the app stores may not have been fully exhaustive, despite the range of search terms utilized and the predefined eligibility criteria.

In addition to the limitations in the app store search, given the rapid pace of app development and lengthy publication process, it might have been appropriate to broaden the search to include grey literature (eg, reports, conference papers). However, given the lack of peer review of grey literature sources, the decided methodology was justified. Finally, the review is based on an electronic search, which was completed in July 2015, and as such the review may not be entirely up-to-date.

Future Research

This review has identified a need for further research, as many of the commercially available apps have not been validated against gold standard measures. Furthermore, many of the validated apps were not studied independently. Thus, further independent validation studies are needed for each available app for ear and hearing assessments. Studies providing a comparison of the accuracy between available audiometry apps would also be useful. The utility of telemedicine techniques, such as video otoscopy using otoscopy apps such as CellScope, could be investigated in field studies. These techniques would involve an offsite ENT, negating the need for such a specialist to be present with the patient, to help deal with the substantial human resource shortage. This additional evidence would assist in making a clear evidence-based decision about which of the apps, if any, could be recommended to be used for screening of ear and hearing conditions.

Most studies in this review focused on populations in high income countries, in which the need for validated smartphone apps still exists; however, we focused on screening for hearing impairment in low-resource settings. This discrepancy highlights the need for further research evidence for populations with DHI living in LMICs, where the greatest burden exists [2]. Finally, it is important to regularly update this review and monitor further app developments, especially for suitable apps to test pediatric populations and those who cannot perform PTA.

Conclusions

There are a number of apps available for ear and hearing assessments; however, very few have been validated in peer-reviewed literature. Of the apps that have been validated, further independent research is required to fully understand their accuracy for detecting ear and hearing conditions. Given the results of this review, audiometry apps cannot be recommended to replace gold standard PTA conducted by an audiologist. However, despite the limited evidence obtained in this review, the portability, accessibility, self-administration, and low-cost nature of ear and hearing apps still offer an exciting opportunity to overcome the key barriers to screening for ear and hearing conditions in LMICs.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Search strategy for EMBASE.

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Multimedia Appendix 2

Summary of apps identified on Google Play and AppStore reviews.

[PDF File (Adobe PDF File), 48KB - rehab_v3i2e13_app2.pdf]

Multimedia Appendix 3

Summary of selected peer-reviewed studies included in the review.

[PDF File (Adobe PDF File), 78KB - rehab_v3i2e13_app3.pdf]

Multimedia Appendix 4

Risk of bias of included studies.

[PDF File (Adobe PDF File), 32KB - rehab_v3i2e13_app4.pdf]

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Abbreviations

ABR: Auditory Brainstem Response
AC: air conduction
BC: bone conduction
dB: decibel
dBA: A-weighted decibels
dBHL: decibels Hearing Level
ENT: ear, nose, and throat
HIV: human immunodeficiency virus
Hz: Hertz
LMIC: low- and middle-income country
OAE: Otoacoustic Emissions
PTA: Pure Tone Audiometry
PTAv: Pure Tone Average
QUADAS-2: Quality Assessment for Diagnostic Accuracy Studies
WHO: World Health Organization

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Original Paper

Internet-Based Exercise Therapy Using Algorithms for Conservative Treatment of Anterior Knee Pain: A Pragmatic Randomized Controlled Trial

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Abstract

Background: Conservative treatment remains the first-line option, and there is significant medical evidence showing that home-based exercise therapy for the treatment of common causes of knee pain is effective. SimpleTherapy created an online platform that delivers Internet-based exercise therapy for common causes of knee pain. The system is driven by an algorithm that can process the user's feedback to provide an adaptive exercise regimen. This triple-armed, pragmatic randomized pilot was designed to evaluate if this telerehabilitation platform is safe and effective.

Objective: We hypothesized that a home-based, algorithm-driven exercise therapy program can be safe for use and even improve compliance over the standard of care, the paper handout.

Methods: After an independent internal review board review and approval, the website trial.simpletherapy.com was opened. Once the trial was open for enrollment, no changes to the functionality or user interaction features were performed until the trial had closed. User accrual to the website was done using website optimization and social media postings tied to existence of knee pain. Consent was obtained online through checkboxes with third-party signature confirmation. No fees were charged to any patient. Patients were recruited online from an open access website. Outcomes were self-assessed through questionnaires with no face-to-face clinician interaction. A triple-arm randomized controlled trial was used with arm 1 being a static handout of exercises, arm 2 being a video version of arm 1, and arm 3 being a video-based, algorithm-driven system that took patient feedback and changed the exercises based on the feedback. Patients used household items and were not supervised by a physical therapist or clinician. Patients were reminded at 48-hour intervals to complete an exercise session.

Results: A total of 860 users found the trial and initiated the registration process. These 860 were randomized, and the demographic distribution shows the randomization was successful. In all, 70 users completed the 6-week regimen (8.1%): 20 users were in arm 1, 33 users in arm 2, and 17 users in arm 3. There were no adverse events reported in any of the 3 arms. All outcomes were self-assessed. No adverse events were reported during or after the trial.

Conclusions: Because only 8.1% of those who enrolled completed the trial, an intent-to-treat analysis did not reach statistical significance in this pilot trial. However, the completion rates are comparable to those of previous online-only trials. Given an early phase trial, no adverse events were reported. Ongoing data collection continues and will form the basis for further data on the efficacy of this intervention.

Trial Registration: Clinicaltrials.gov NCT01696162; https://clinicaltrials.gov/ct2/show/NCT01696162 (Archived by WebCite at http://www.webcitation.org/6lM8jC7Gu)

Introduction

Knee pain is one of the most common conditions seen by orthopedic surgeons and primary care physicians with an estimated prevalence of 15% to 45% of the population. The causes of knee pain remain diverse, with the most common cause being osteoarthritis [1,2]. Conservative treatment remains the first-line option, and there is significant medical evidence showing that home-based exercise therapy for the treatment of common causes of knee pain is effective [3,4].

The use of the Internet to provide wide-reaching medical therapies is increasing. The term "telemedicine" has been employed to signal this widespread interest. Within telemedicine is a subcategory called "telerehabilitation." The American Telemedicine Association defines telerehabilitation as "the delivery of rehabilitation services via information and communication technologies." The type of information and communication technologies can vary widely, from videoconferencing to video delivery. In some stroke studies, videoconferencing techniques were shown to be efficacious and feasible [5,6]. However, research on the application of telerehabilitation and specifically the delivery of asynchronous instructional videos for common musculoskeletal conditions such as knee pain is lacking, and the effectiveness of the application remains unknown.

SimpleTherapy created an online platform that delivers Internet-based exercise therapy for common causes of knee pain. The system is designed as a stand-alone intervention capable of expanding access as a cost-effective option to physical therapy and can complement or replace visits to a physical therapists for certain populations. The core value of the platform is an algorithm that can process the user's feedback to provide an adaptive exercise regimen. This triple-armed, randomized controlled pilot was designed to evaluate if this telerehabilitation platform is safe and effective. Our hypotheses were that (1) unsupervised, Web-based exercise therapy could be performed safely and would relieve anterior knee pain in a properly screened population and (2) this modality would be preferred in some ways over traditional, in-person physical therapy.

Methods

Recruitment

After an independent internal review board review and approval (Salus Internal Review Board Protocol #413), the website trial.simpletherapy.com was opened [7]. Once the trial was open for enrollment, no changes to the functionality or user interaction features were performed until the trial had closed. The trial was registered with ClinicalTrials.gov [NCT01696162]. User accrual to the website was done using website optimization and social media postings tied to existence of knee pain. Consent was obtained online through checkboxes with third-party signature confirmation. No fees were charged to any patient. Patients accessed the site through a computer connected to the Internet without supervision. Patients were recruited online from an open access website. Outcomes were self-assessed through questionnaires with no face-to-face clinician interaction. Patients were not required to be part of an organization or other diagnosis subset. No external funding was used for this study. The trial was funded by SimpleTherapy LLC.

Onboarding

When potential users landed on the website, they underwent a 3-part series of evaluations to ensure qualification for participating in unsupervised exercise therapy. The user would be asked to fill out the Physical Activity Readiness Questionnaire (PAR-Q), a questionnaire recommended for use by the American College of Sports Medicine to help screen participants safe for exercise (Multimedia Appendix 1). If the participant answered all of the questions appropriately, they would move onto the second screen. The participants were asked whether a doctor or medical professional had said they were safe for exercise therapy. If the answer was yes, the name of the medical professional was recorded, and the user entered into the next phase of the system. If the answer was no, the user was interviewed over the phone by a physician during which a set of questions called the Knee Exercise Eligibility Score (KEES) was used (Multimedia Appendix 2). The questions were asked verbatim with request for further clarification of the potential user's answer. Those participants who answered these questions correctly were then entered into the next phase of the system. Computer literacy was an assumed *de facto* eligibility criterion. In order to be eligible for participation in the trial, a patient had to answer all screening questions of the PAR-Q and KEES correctly.

Once the user was screened and deemed appropriate for safe participation, the user would register. Basic demographic information was collected including gender, age, height, and weight. Participants were asked to read and electronically sign a consent form outlining the clinical trial and all of the associated risks and benefits (Multimedia Appendix 3). A third-party website was used to obtain electronic signature verification. After consenting, the patient was allocated in a parallel design into three arms: arm 1, which provided 6 static exercises for knee pain viewable only on the computer screen, meant to mimic the handouts given to patients discharged from traditional physical therapy; arm 2, which provided the same 6 exercises offered in arm 1 in video form; and arm 3, the SimpleTherapy video-based platform, which delivered a progressive sequence of 6 exercises per visit based on user input from the prior exercise session.

Software code using a random number generator performed the randomization in a 1:1:1 ratio. This randomization code was not tampered with once the trial had been launched. Investigators were not involved in the randomization process. At the 3-month mark, the number of users within each arm was assessed to ensure proper allocation.

User Engagement

Users were then asked to perform the exercises 3 times per week for 6 weeks. Surveys were gathered from the participants at the initiation of the program and 6 weeks after the program started (Multimedia Appendix 4). The exercises were selected by orthopedic surgeons, and patients gave feedback on each exercise after a session (consisting of 6 exercises). The feedback

choices were "too easy," "just right," "too hard," and "it hurt." The next session's exercises were selected by an algorithm that incorporated user feedback. Thus each exercise session was novel to patients with respect to their experience from the previous session. The videos were designed to contain the coaching of a physical therapist or orthopedic specialist regarding form, function, and experience of each exercise. All communication was via email or on-screen instructions and was asynchronous. Patients were reminded via email every 48 hours to perform a session. Clinicians monitored pain levels and feedback but did not directly communicate with patients except to answer email questions. Compliance was measured automatically based on log-in time and feedback completion.

Compliance and pain levels were assessed at 3, 6, and 12 weeks in all 3 groups. Compliance logs were monitored in a blinded fashion, and all pain levels were self-reported using a visual analog scale and completed online without clinician assistance or guidance. The visual analog scale was used due to its long-term clinical reproducibility and accuracy. Questionnaires were not validated prior to trial implementation. Questionnaires were designed by consensus of a team of orthopedic surgeons and physical therapists.

Patients were not blinded from their intervention. A software developer who is not an author was also not blinded to each patient's allocation. All authors were blinded through the analysis of data using spreadsheets with compliance and pain data without labels to each column. Only when statistical significance was calculated were investigators made aware of arm allocation. No privacy breaches or technical problems occurred. An adverse event was defined as any user who reported an acute inability to perform the exercises (eg, was able to extend the knee and then was unable to due to a mechanical block). A serious adverse event was defined as a user who during the trial period was required to be seen in an emergency department or hospital for the knee pain or had surgical intervention for the knee pain.

Significant attrition of users during the study occurred. As such, intention-to-treat analysis was not conducted. Those included in the statistical analysis were those users who completed the program and provided the required outcome measure. This we deem a "completion analysis," although this does not represent a truly randomized sample. Student t tests were conducted to compare mean pain and University of California Los Angeles (UCLA) activity scale scores within each arm at the initial, 3-week, and 6-week time points. A Cohen d was calculated to evaluate for effect size. Analysis of variance was performed to evaluate whether arm allocation was associated with reported pain scores and changes in pain score at 6 weeks. $P<.05$ was considered statistically significant.

Results

Randomization

A total of 8525 individuals landed on the clinical trial website. Of these, 860 users initiated and completed the registration process. These 860 were randomized, and the demographic distribution shows the randomization was successful (Table 1). The final cohort of users who were analyzed is shown in the flow diagram in Figure 1. An attrition flow diagram indicating usage patterns is shown in Figure 2.

Table 1. Randomization results of users.

	Arm 1 n=286	Arm 2 n=290	Arm 3 n=284
Age (years)	52.1	51.6	51.7
Gender			
Male	111	104	111
Female	175	186	173
Weight (lb)	185.4	188.2	194.0
Body mass index (kg/m^2)	28.0	29.2	29.1

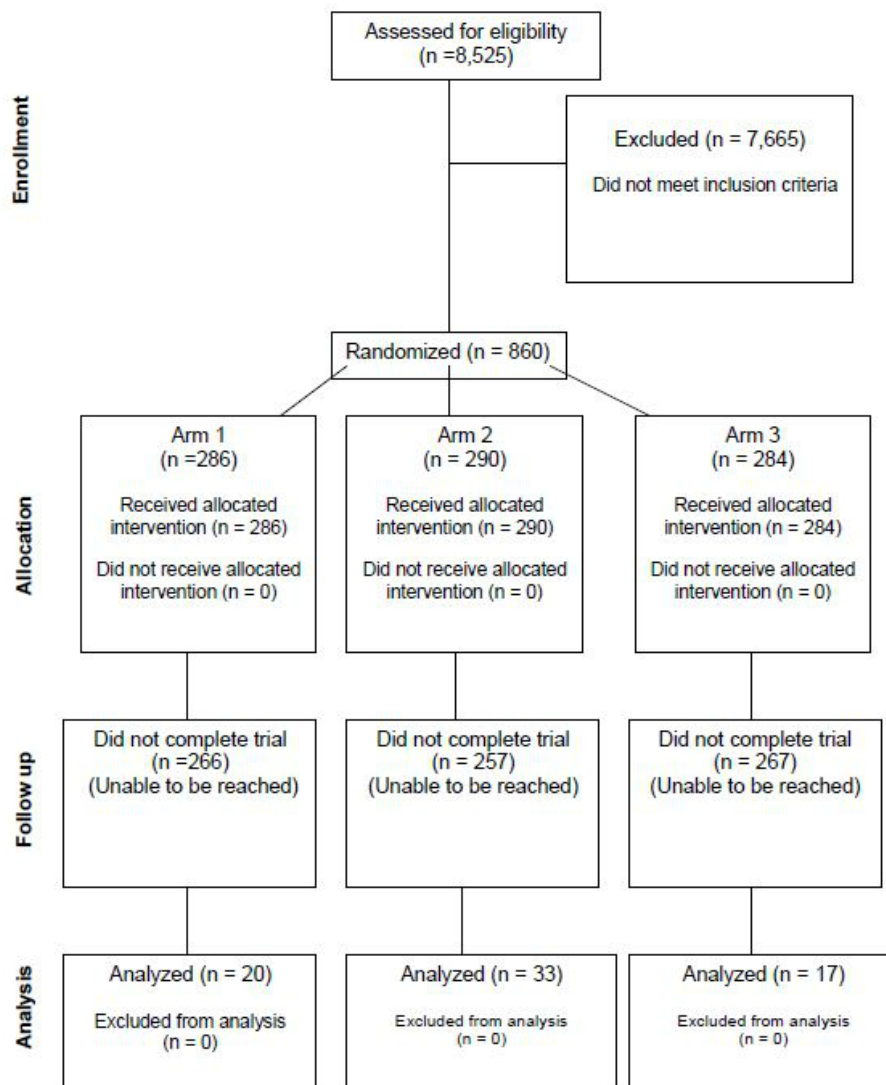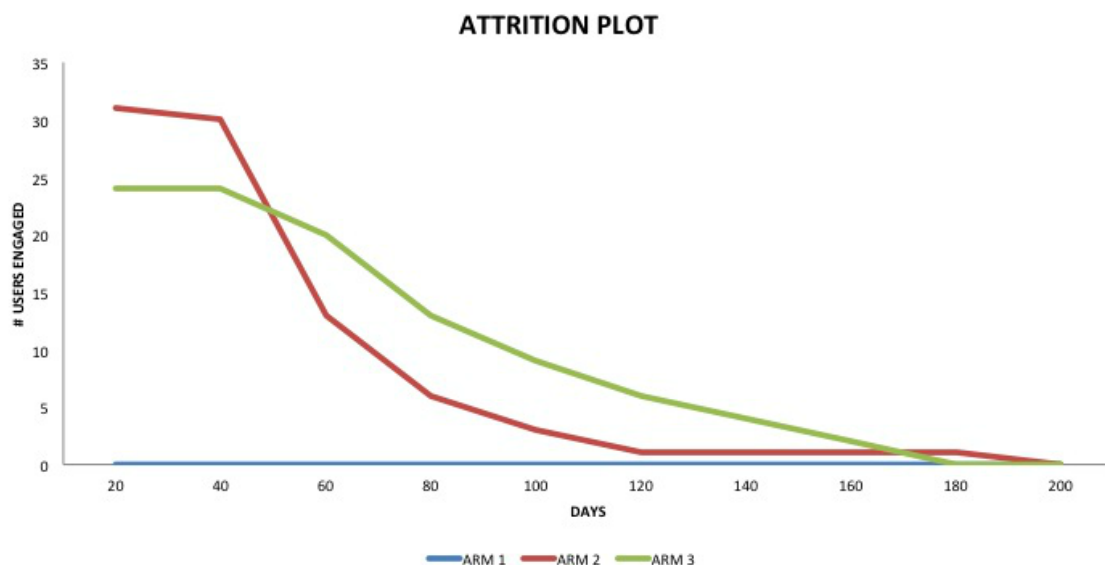**Figure 1.** Trial onboarding and allocation flow.

Figure 2. Attrition plot.

Arm 1

A total of 286 users were randomized to arm 1. No users in arm 1 provided a 3-week pain or UCLA score; 20 users provided an initial and 6-week pain and UCLA activity scores. The mean initial and 6-week pain scores were 3.9 (SD 1.7, 95% CI 3.1-4.7) versus 3.7 (SD 1.8, 95% CI 2.8-4.6) (P=.69), respectively. Cohen d=0.11. The mean initial and 6-week UCLA activity scores were 6.0 (SD 2.1, 95% CI 5.0-7.0) versus 6.6 (SD 2.1, 95% CI 5.6-7.6) (P=.23), respectively. Cohen d=0.29.

Arm 2

A total of 290 users were randomized to arm 2 with 27 users reporting an initial and 3-week pain and UCLA activity scores. The mean initial and 3-week pain scores were 4.6 (SD 1.9, 95% CI 3.9-5.3) versus 3.8 (SD 2.2, 95% CI 2.9-4.7) (P=.06), respectively. Cohen d=0.36. The mean initial and 3-week UCLA activity scores were 6.0 (SD 2.2, 95% CI 5.1-6.9) versus 6.4 (SD 1.9, 95% CI 5.6-7.2) (P=.27), respectively. Cohen d=0.19.

A total of 33 users reported an initial and 6-week pain and UCLA activity scores. The mean initial and 6-week pain scores were 4.8 (SD 1.8, 95% CI 4.2-5.4) versus 4.4 (SD 2.5, 95% CI 3.5-5.3) (P=.45), respectively. Cohen d=0.18. The mean initial and 6-week UCLA activity scores were 6.0 (SD 2.3, 95% CI 5.2-6.8) versus 6.1 (SD 2.4, 95% CI 5.3-6.9) (P=.8), respectively. Cohen d=0.04.

Arm 3

A total of 284 users were randomized to arm 3; 17 users reported an initial and 3-week pain and UCLA activity scores. The mean initial and 3-week pain scores were 4.4 (SD 2.2, 95% CI 3.3-5.5) versus 3.9 (SD 2.0, 95% CI 2.9-4.9) (P=.40), respectively. Cohen d=0.24. The mean initial and 3-week UCLA activity scores were 6.1 (SD 2.2, 95% CI 5.0-7.2) versus 6.8 (SD 2.5, 95% CI 5.5-8.1) (P=.14), respectively. Cohen d=0.30.

A total of 17 users reported an initial and 6-week pain and UCLA activity scores. The mean initial and 6-week pain scores were 4.5 (SD 2.1, 95% CI 3.4-5.6) versus 3.0 (SD 2.1, 95% CI 1.9-4.1) (P=.009), respectively. Cohen d=0.7. The mean initial and 6-week UCLA activity scores were 6.6 (SD 1.9, 95% CI 5.6-7.6) versus 6.6 (SD 2.0, 95% CI 5.6-7.6) (P>.99), respectively. Cohen d=0.0.

Arm Allocation and 6-Week Pain Scores

One-way analysis of variance was conducted to compare the effects of arm allocation to reported pain score at 6 weeks as well as the change in pain score from the initially reported pain score. The mean reported pain score between groups was not significant (P=.11). The mean changes in pain score achieved by arms 1, 2, and 3 were –0.2 versus –0.4 versus –1.5, respectively. There was not a significant effect of arm allocation and change in pain score at the P<.05 level ($F_{2,67}$=1.34, P=.27).

Usability and Adverse Events

During the study, no adverse events were reported from the users. When asked whether the users enjoyed the use of this telerehabilitation platform better than in-person physical therapy, 79% (19/24) responded yes in arm 1 versus 89% (32/36) in arm 2 versus 96% (26/27) in arm 3. When asked if during the trial the user required other medical interventions such as visiting a doctor or physical therapist or receiving a knee injection, 54% (13/24) of users in arm 1 responded yes versus 22% (8/36) of users in arm 2 versus 22% (6/27) of users in arm 3 (Table 2).

Users chose the following reasons for trying the telerehabilitation platform: 8 chose "effectiveness," 19 chose "ease of use," 28 chose "ease of access," 15 chose "cost," and 17 chose "other." Two users who chose "other" typed in their reasons: "Made sense and I could do it on my schedule" and "Doctors are too interested in invasive treatments."

Table 2. Number of users who needed further medical intervention.

	None	Visited physical therapist	Visited doctor	Received injection	Med resource	%
Arm 1 (n=24)	11	3	10	0	13	54
Arm 2 (n=36)	27	0	6	2	8	22
Arm 3 (n=27)	0	0	6	0	6	22

Discussion

Principal Findings

Internet access and its use in health care are becoming more prevalent in the United States. The Pew Research Center recently reported that 87% of Americans use the Internet and 77% of Americans have searched online for health-related information, with the most commonly searched topics related to specific diseases or conditions and treatments. This is an increase from 62% when the survey was conducted in 2001. More than half of users aged 50 to 64 years have searched online for health information. Lastly, 28% of users went online to obtain a diagnosis. All signs point to the Internet becoming a major factor in how people access health care [8].

We hypothesized that a video-based, asynchronous Internet-only intervention could be safe and effective for patients with anterior knee pain. Safety was the number one goal of this trial, and we found that no adverse events were recorded in any of the arms. Arms 1 and 2, handouts provided to users after in-person therapy sessions and YouTube videos found on the Internet, respectively, are current standards of care accessible to the population. Comparatively, the lack of reported adverse events in the implementation of a user-feedback–based telerehabilitation algorithm (arm 3) supports the safety in providing such a service. Further, as no clinician guidance or oversight was provided, the results are generalizable to a comparable population with similar technology understanding and motivation.

We used self-reported pain scores and the UCLA activity score as a gauge of the effectiveness of the programs. The most

striking finding was that after 6 weeks, users who were in arm 3 reported the lowest mean pain score compared to arm 1 and arm 2. At 3 weeks, there was no statistical difference in the mean pain score reported in arm 2 and arm 3, suggesting that the program is most effective at a minimum of 4 weeks. Furthermore, the largest reported effect size was in arm 3 at 6 weeks, supporting the idea that a user-driven telerehabilitation for anterior knee pain can be a more effective method compared to the current standards.

When looking at self-reported UCLA activity scores, there was no difference between the 3 arms, suggesting that the achieved reduction in pain did not necessarily improve activity scores. However, the UCLA activity score was designed to assess activity levels after total joint replacement. These patients have significant multicompartmental osteoarthritis and poor prejoint replacement function, allowing the UCLA activity score to capture a larger difference. Comparatively, our users' mean starting UCLA score was 6, which correlates to users already participating in moderate activity. It may not be able to capture the subtle changes in activity that improving anterior knee pain could cause. Another activity scale may have to be employed in future studies to capture this improvement.

There was no significant difference in the changes in pain scores at 6 weeks as a function of the arm allocation. When closely looking at the absolute change, however, we find that users in arm 3 reported an average 1.5-point decrease in pain score, compared to arms 1 and 2, which each showed a less than 1-point change. This indicates a trend toward the user improving from a moderate to mild level of pain, which is clinically relevant. Further, change is unrelated to any significant increase or decrease in the UCLA activity scores, suggesting the decreasing pain level observed is directly related to the exercise regimens.

Lastly, users in arm 3, compared to arms 1 and 2, enjoyed using the program more. This is likely related to the user feeling engaged and being able to direct their own progression of exercises. Users in arm 3 showed a more than 50% reduction in the need for medical intervention such as an injection or a visit to a doctor compared to arm 1. This significant reduction in health care utilization while involved in the program is a valuable contribution to the medical community since health care costs are rising. Exercise telerehabilitation, delivered via a user feedback system, can reduce unnecessary doctor and physical therapy visits while continuing to deliver effective care.

Limitations

Our study, however, is not without weaknesses. Only 8% of users who registered completed the 6-week system. Regularly, the difficulty of running a purely online clinical trial is evident in attrition rates. McAlindon [9] ran an online glucosamine trial for knee osteoarthritis. Patients were randomized to either a drug arm or placebo arm. A total of 1200 applicants signed up for the trial, of which 200 (16%) completed it. Although enrollment and retention were better than our current study, they spent US $950 per participant for recruitment and follow-up, which was far higher than the US $60 per person our study spent [9]. What the McAlindon study concluded was that conducting online trials was feasible and effective. The ability of our study to attract 860 users to register is comparable with another study by Formica [10]. Further, this platform was version 1.0 with few user engagement functions incorporated. We expect that with future product development, accrual and retention numbers will be significantly improved.

Secondly, our study is not sufficiently powered to evaluate efficacy in pain reduction. However, even with these small numbers, our study suggests increased effectiveness in reducing pain when users are engaged in the video user-feedback–based platform. We anticipate that future studies with greater power will demonstrate greater effectiveness. Thirdly, our data analysis was conducted as a completion analysis. Only those who provided the full data were deemed appropriate for the final analysis. This does not make this a true randomized sampling and introduces bias.

Conclusion

In conclusion, our pilot study showed that the algorithm-driven, user-feedback–based telerehabilitation platform SimpleTherapy is safe and can be a pragmatic alternative to helping improve anterior knee pain. Since the trial, the intervention has undergone a myriad of changes to the interface; verbiage explaining the offering, reminders, and content; and the algorithm logic. Although future studies are required, the findings of this study support the continued development of this new telerehabilitation platform. We will continue to publish outcomes regarding the platform in multiple other body areas and populations. These studies are currently ongoing.

Conflicts of Interest

Dr Tae Won Kim is a cofounder and chief research officer of SimpleTherapy and holds an equity stake in the company. Dr Andre Nicolas Gay is a cofounder and chief medical officer of SimpleTherapy and holds an equity stake in the company. Arpit Khemka is the chief technology officer of SimpleTherapy and holds an equity stake in the company. Dr Jonathan P Garino is an advisor of SimpleTherapy and holds an equity stake in the company.

Multimedia Appendix 1

Physical Activity Readiness Questionnaire.

[PDF File (Adobe PDF File), 52KB - rehab_v3i2e12_app1.pdf]

XSL•FO

RenderX

Multimedia Appendix 2

Knee Exercise Eligibility Score.

[PDF File (Adobe PDF File), 24KB - rehab_v3i2e12_app2.pdf]

Multimedia Appendix 3

Informed consent document.

[PDF File (Adobe PDF File), 83KB - rehab_v3i2e12_app3.pdf]

Multimedia Appendix 4

Questions for initial and 6-week feedback.

[PDF File (Adobe PDF File), 33KB - rehab_v3i2e12_app4.pdf]

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Abbreviations

KEES: Knee Exercise Readiness Score
PAR-Q: Physical Activity Readiness Questionnaire
UCLA score: University of California, Los Angeles score

Review

Studies Involving People With Dementia and Touchscreen Technology: A Literature Review

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Abstract

Background: Devices using touchscreen interfaces such as tablets and smartphones have been highlighted as potentially suitable for people with dementia due to their intuitive and simple control method. This population experience a lack of meaningful, engaging activities, yet the potential use of the touchscreen format to address this issue has not been fully realized.

Objective: To identify and synthesize the existing body of literature involving the use of touchscreen technology and people with dementia in order to guide future research in this area.

Methods: A systematized review of studies in the English language was conducted, where a touchscreen interface was used with human participants with dementia.

Results: A total of 45 articles met the inclusion criteria. Four questions were addressed concerning (1) the context of use, (2) reasons behind the selection of the technology, (3) details of the hardware and software, and (4) whether independent use by people with dementia was evidenced.

Conclusions: This review presents an emerging body of evidence demonstrating that people with dementia are able to independently use touchscreen technology. The intuitive control method and adaptability of modern devices has driven the selection of this technology in studies. However, its primary use to date has been as a method to deliver assessments and screening tests or to provide an assistive function or cognitive rehabilitation. Building on the finding that people with dementia are able to use touchscreen technology and which design features facilitate this, more use could be made to deliver independent activities for meaningful occupation, entertainment, and fun.

Introduction

Dementia is an incurable syndrome caused by a chronic or progressive disease of the brain [1]. It has currently affected more than 46 million people worldwide, and this number is predicted to increase to 131.5 million by 2050 [2]. Dementia can affect multiple areas of cognitive functioning, including memory, thinking, comprehension, learning capacity, orientation, judgment, and language, and many people experience an impact on motivation, social behavior and emotion [1].

Lack of activity, or boredom, is frequently reported by people with dementia, whether they are still living at home or have moved into care services [3,4]. Engaging in meaningful activities can decrease boredom and increase positive emotions [5].

Facilitating people with dementia to engage in independent activity through the selection of appropriate activities can be highly beneficial as it promotes autonomy, thereby avoiding dependence on family members or formal caregivers [6].

The use of technology in dementia care is growing [7], but it has been observed that technological solutions developed for people with dementia have been centered around "assistive" devices [8-10]. Ironically, these applications are typically not intended for use by the people with dementia, but rather by family members or formal caregivers [11]. Furthermore, there has been some debate surrounding the use of technological assistance in this context, particularly in cases involving the monitoring or control of individuals through "assistive" devices, such as electronic tagging [8]. This highlights the need for careful consideration when introducing technological devices as aids for people with dementia, and to be clear from the outset who the "assistance" is actually for.

The increased availability of touchscreen technology devices in everyday life, such as smartphones and tablets, has led to an increased consideration by health care professionals and researchers of their potential suitability for people with dementia [12]. This trend is set to continue as people are being diagnosed with dementia at a younger age, and coming generations will be more familiar with computer technology [13]. It has been suggested that the touchscreen format is a more effective solution as it makes less demand of hand-eye coordination when compared with a desktop computer using a mouse and cursor [14]. Therefore, the intuitive nature of touchscreen devices presents an opportunity for their application with people with dementia as the intended users of the technology, and for whom the benefits may be experienced directly. For this potential to be realized, the design of simple and accessible software should be considered a priority.

This review presents an overview of the ways touchscreen technology has been used with people with dementia since its invention to the present generation of touchscreen devices, addressing the questions listed in Textbox 1.

Textbox 1. Questions addressed by the literature review.

- In which contexts has touchscreen technology been used by people with dementia?
- For what reason was touchscreen technology chosen?
- Which forms of hardware and software were used?
- Is there any evidence that people with dementia were able to use touchscreen technology independently?

Methods

A systematized review [15] of the literature was conducted on the use of touchscreen technology with people with dementia.

The following search terms, including Boolean operators (eg, AND, OR) and truncation symbols (denoted by *), were used for this review: (dementia) OR (Alzheimer*) AND (touchscreen) OR (touch screen) OR (tablet computer) OR (tablet device) OR (smartphone) OR (smart phone) AND (app*) OR (activit*) OR (game*) OR (gaming).

The following electronic databases were accessed for this review, selected due to their content being relevant to the subject area: Medline via Web of Science; PsychINFO via Ovid SP; ProQuest; PubMed; CINAHL via EBSCO; and Cochrane. The search was extended to include references of relevant articles and existing articles in the researcher's reference management database. The literature search was conducted between July 20 and August 7, 2015.

During screening, records were included or excluded based on the following criteria: Language: English, Participants: human with dementia, and Technology: any featuring a touchscreen interface.

The search protocol described above originally resulted in 121 references being returned through the database searches and 12 additional references through other sources or hand searching. Duplicate articles were removed, resulting in a figure of 95. Subsequently, articles were removed having been reviewed against the inclusion and exclusion criteria, based on their title (19) or abstract (21). This resulted in 55 articles being obtained as full-text documents. Having read all these articles, a further 10 were excluded due to not meeting the inclusion and exclusion criteria; either because the studies did not actually involve people with dementia or because a touchscreen interface was not featured. In total, 45 articles were included for the final review. Figure 1 presents the flow diagram of the search procedure (adapted from [16]).

Figure 1. Flow diagram of search procedure.
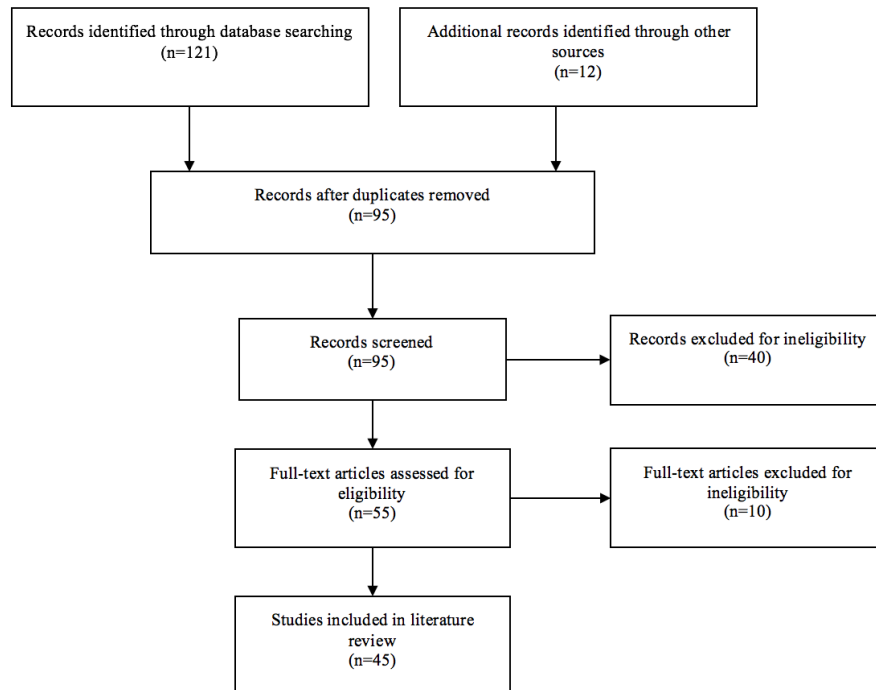
Results

Overview of Results

Forty-five articles met the inclusion criteria and were included for this review. Multimedia Appendix 1 presents the summarized results of the review, and information from these articles has been collated to provide an overview on this topic, organized according to the questions outlined in Textbox 1.

Contexts of Use

A total of 3 broad categories of touchscreen technology utilization were identified during the review: (1) assessment and screening (14 articles); (2) assistive technology and cognitive rehabilitation (24 articles); and (3) leisure activities (9 articles). Two papers contained information pertaining to both an assistive device and a leisure activity and were counted in both categories. Multiple papers within both the assistive and leisure categories described the same devices or software, which is highlighted. Each of these categories have been discussed in detail. It is worth noting that the majority of papers in the "assessment and screening" category mostly describe the touchscreen device as a piece of equipment used to deliver a test, and rarely discuss the impact of selecting the specific technology.

Assessment and Screening

The first reported use of touchscreen technology with people with dementia was in 1986 [17], where the use of a touch-sensitive screen was compared with a conventional computer monitor with a peripheral response device to deliver 2 cognitive assessments or screening tests. In the early 1990s, 2 articles described the incorporation of touchscreen technology into cognitive assessments: the Cambridge Neuropsychological Test Automated Battery (CANTAB) [18] and the French-language Examen Cognitif par Ordinateur (ECO) [19].

Touchscreens have continued to be used for these purposes, evidenced by more recent examples delivering tests of global cognition [20] or batteries of cognitive tests [21-23] for the detection of dementia or mild cognitive impairment (MCI).

In addition to global cognitive assessment, several articles reported the use of touchscreen technology to deliver tests of specific cognitive functions: visual attention [24], working memory [25], executive functioning [26], and visuomotor skills [27,28]. The remaining article in this theme [29] used computerized maze tests presented on a touchscreen computer to predict driving performance.

The vast majority of these articles developed original tests for the touchscreen format such as the Edinburgh Dementia App [23] and the Touch Panel-type Dementia Assessment Scale [22]. Only one study reported the adaptation of an existing test; the sparse-letter display test [24], which had previously been presented on a computer but not using the touchscreen format.

Assistive Technology and Cognitive Rehabilitation

The majority of articles describe the use of touchscreen technology to provide an assistive function for the person with dementia or their caregivers, or to present interactive cognitive exercises.

Five of the reviewed papers discussed the Computer Interactive Reminiscence and Conversation Aid (CIRCA), a communication support tool using digital reminiscence materials to stimulate conversation between the person with dementia and a conversation partner [30-34]. Several other studies also used reminiscence materials presented on a touchscreen interface to provide other assistive functions [9,35-39]. The use of touchscreen technology to support therapists was also evident in the context of art therapy and occupational therapy [40-42]. Several articles reported the use of touchscreen technology to address multiple activities of daily living (ADL) for people with

dementia [43-46], including calendars, diaries, video calling, and location tracking. Although different terminology was used to describe their focus, the remaining articles categorized in this section used touchscreen technology to present cognitive exercises to people with dementia, either using originally designed software [47-51] or existing software [52].

Leisure Activities

Several of the aforementioned articles have featured games or leisure activities; however, these have been designed to assess cognition [21,26], provide cognitive stimulation [37,45], or to assist in the delivery of therapeutic interventions [40,41]. Very few studies focused on games or activities purely for entertainment or leisure purposes.

Three of the reviewed articles described "Living In the Moment" (LIM) [31,53,54], a suite of touchscreen games and activities that at various stages of the project included virtual environments, skill games, games of chance, and creative activities, the common factor being that they were all designed in partnership with people with dementia. Original design was also utilized in 3 articles; 2 focusing on musical creativity [55,56] and 1 to provide enjoyable activity either independently or in a group setting [39]. The remaining articles included in this section investigated the use of existing touchscreen activities, rather than those developed specifically for people with dementia [5,10,13].

Touchscreen Technology Selection

Many, although not all, reviewed articles reported why they had chosen touchscreen technology. The reasons can be summarized into the following categories: the intuitive control method (9 articles), practicalities of administration (12 articles), the ability to customize and adapt (4 articles), and the multifunctional nature of the devices (10 articles). These reasons are explored further.

Intuitive Control

The touchscreen control method is widely regarded as intuitive [5,10,17,47] and easy to use [25,39], making it highly advantageous for people with dementia. Eliminating the need for external input devices, for example, a keyboard and a mouse, is beneficial as it reduces the cognitive load required to input information [10,17,24,47]. This was addressed directly in Tippett & Sergio [28], where the performance of people with dementia on a visuomotor test was highest when the touch-sensitive interface was placed directly over the computer monitor as opposed to when placed in front or to the side. A similar method was used in the study by Carr et al [17], who reported that participants in the group using an external response board would sometimes intuitively reach out to touch the screen. An alternative example can be seen in Ott et al [29], where participants were required to use a stylus to trace a path through the maze in order to replicate the "natural" method of using a paper and pen.

Practicalities

In administering cognitive tests, touchscreen computers are seen as a more practical solution for a number of reasons. These include increased accuracy of data input [18,25,29], flexible but also standardized administration [25], reduction in administration bias by avoiding experimenter effects [20], financially efficient implementation [22,25,29], and the wide availability of this technology in health care settings [23].

In addition, the use of touchscreen computers reduces the practical requirement for members of staff to prepare and manage multiple materials, for example, reminiscence materials [30,33,38,42,52]. This is highlighted as a potential time-saving measure for often busy clinical staff [41].

Customization

Programs and apps presented on touchscreen devices can be designed to facilitate customization, which allows for easy adaptation and consequently they can be responsive to the needs of the users [13,25,37,40,41]. Presenting customization options within programs in an accessible format allows a caregiver or therapist to tailor the program to each individual [40,41]. This is particularly beneficial for people with dementia as programs can become responsive to change in their cognitive functioning and abilities over time. For example, with games, it is important to include difficulty options so that each player can find a suitable entry point [37]. Another benefit to customization highlighted in the literature is with regards to administering cognitive assessments, where being able to easily manipulate experimental parameters can allow for repeat testing while avoiding learned responses [25].

Multifunctional Use

A further advantage of touchscreen devices such as tablets and smartphones is that they can provide a wide range of functions for the user. As is reflected in the literature, these devices can address the multiple needs of people with dementia, for example, increasing socialization, providing memory prompts, facilitating activities, and delivering educative tools [10,13,36,37,44]. During reminiscence activities, for example, photographs and music can be accessed simultaneously, increasing their potential to trigger memories [38]. The fact that a wide variety of downloadable apps can be added to such devices only increases the availability of these functions [5,52]. It is also reported that built-in and attachable accessories, for example, cameras [35] and sensors [48] can even further increase the functionality available through these devices.

Hardware and Software

Where reported in the literature, information related to the hardware and software used in the reviewed studies is discussed here. The information that was judged as most relevant was screen size and the model of tablet devices or smartphones and their operating system (OS). To allow for easier comparison, all screen sizes have been converted into inches (diagonal), if not already presented in this unit.

Screen Size

The touchscreen devices used in the reviewed articles range in size, largely determined by whether a monitor (largest), tablet, or smartphone (smallest) was used. Fourteen articles reported and specified using a touchscreen monitor or a touch-sensitive interface in combination with a monitor [17,21-25,28-30,33,34, 40, 46,51,53]. Screen size in these studies ranged from 14″ to

32˝ with a mode size of 20˝. Six articles reported and specified using a tablet device, all with a screen size of 9.7˝ [5,10,39,42,52]. Three articles reported and specified using a mobile smartphone, with sizes of 2.8˝ [46], 3.5˝ [13], and 3.8˝ [43].

With regard to size, a larger screen can be advantageous for people with cognitive impairment, particularly when there is the addition of a visual impairment [56]. This would support the use of monitors, however the portability of tablet devices and smartphones is also seen as advantageous [25], as is the availability and ease of access to downloadable apps [5,52]. There should be consideration for the suitable placement of tablet devices during interactions, given their size and weight, with the recommendation of placing the device on a surface (eg, table) and raising the height to a comfortable level for the user to reduce muscle stress [25]. Finally, the small size of smartphone screens has been highlighted as a potential issue for people with dementia during user testing [43].

Models and Operating System

All the studies that reported using tablets, and specified which device, used an Apple iPad [5,10,39,42,52]. In discussing the reason for selecting an iPad, and therefore the Apple iOS, Lim et al [10] commented on its ease of use when compared with Android OS or Windows OS, a factor that is particularly important where the intended users are people with dementia. Android [48], Windows [43] and Apple [13] were each used as the OS in studies that specified smartphone use. In the study by Zmily et al [48] involving the use of near-field communication (NFC) technology, the Android OS was selected primarily because, at the time, the majority of mobile devices with NFC functionality used Android. Commenting on app development, Pang and Kwong [37] stated that apps designed for people with dementia should be developed for both Apple and Android to allow people the choice in what device to purchase, particularly in relation to cost.

Independent Use

The use of touchscreen technology in the reviewed articles involved a range of interaction levels between the people with dementia and the devices. Supported use was common, that is, where the person with dementia interacts with the technology in the presence of a clinician or carer, where input may be encouraged or shared [23,28,30,33,34,38,41,42,56]. Many studies involved devices that were designed for independent use or used existing devices that were utilized independently by the person with dementia [9,10,13, 20,22,24,26,32,35, 37,43-45,47,53,54]. In some cases, independent use was successful. For example, Lim et al [10] reported that half their participants were able to use an iPad independently for leisure activities, and a quarter were able to store and charge the device without support. Participants using the LIM games were left alone to interact with the touchscreen and the majority were able to navigate the system independently, even at the prototype stage [53]. Two thirds of participants were able to use the Companion system independently, although the remaining third were not, with the authors citing personal motivation and physical impairment as potential factors [9]. Although the "COGKNOW" system was designed for independent use by

people with dementia, in practice it was found that those people who lived with a partner tended to rely on them for support [44]. Several articles reported positive factors for people with dementia associated with independent use of the touchscreen devices, including relaxation [9], enjoyment [9,45,54], autonomy [9,45,54], motivation [26], socialization [32], and engagement [54].

In reviewing the articles for evidence of independent touchscreen use, key factors emerge relating to the potential for successful outcomes; namely, training, use of prompts, integrated feedback, and visual design. Each of these factors will now be discussed.

Training

There were many examples of studies using a training or demonstration phase before participants were expected to use a device independently [13,24-26,28,48,57]. In several cases, this involved the researcher or clinician demonstrating or instructing device use, followed by a familiarization phase where the participant would be observed using the device so that their understanding could be verified [24,25,28,57]. In one example using this method, the familiarization phase would only end once the clinician was satisfied that the participant could use the device independently, up to a maximum of 8 trials [28]. In another example, a simplified version of the actual trial test was used during this phase to prevent learning bias [24]. Zmily et al [48] predicted that this demonstration would be necessary, given that the target population is generally less experienced using computer devices, which was supported in their results. In their case study, Astell et al [13] concluded that the participant's successful adoption of several forms of new technology was achieved because of the high level of appropriate training and support delivered by the researcher, which will not always be feasible.

Prompts

Many of the articles described the use of integrated prompts within their software to direct or regain the attention of the user, although the outcomes are varied. In developing the LIM games, the research team considered and experimented with many different forms of prompts including text boxes, animations, the spoken voice, and an avatar [53,54]. The idea of an avatar was rejected due to the potential for it to be overly distracting, while the spoken voice prompt was implemented but often ignored (possibly due to its synthetic nature being unrecognizable), or relied on too heavily, resulting in a passive experience where the user would just wait until they next received an instruction. In contrast, the text boxes and animations were found to be more successful, with the conclusion being that overly intrusive prompts were unnecessary [54]. Other studies reported using spoken prompts in their programs [20,22,35,48], either through human recording or synthesized text-to-speech. Inoue et al [22] reported that participants were more likely to find prompts useful in the earlier stages of dementia. In Meiland et al [44], the use of visual and audio prompts was reported to be largely unsuccessful, with users either not noticing the prompt or ignoring it.

There was also variety between the studies in how prompts were triggered, for example, following a period of inactivity [53,54]; following a predetermined number of errors [26]; or using artificial intelligence to detect a reduction in engagement, measured through eye-tracking and screen touches [41].

Feedback

The importance of feedback in response to user input when designing or selecting touchscreen software for use by people with dementia was discussed in several articles [24,54,56]. Feedback should involve either an animation or sound effect (or both) contextual to the input and should be immediate, to acknowledge the user interaction [54].

Visual Design

When designing interfaces specifically for people with dementia on touchscreen devices, the reviewed literature recommends the avoidance of complexity [35,37,40,56]. The number of steps to navigate or achieve goals should be kept to a minimum [35-37,56], with uncluttered interfaces [56], and the consistent use of colors and icons so that users have a sense of context [35-37]. The traditional design of apps may be problematic for people with dementia, with drop-down menus and ambiguous icons without text, and therefore should be avoided [36,37]. Icons, text, and graphics should be appropriately sized for people who may have visual impairment [36,37,47] and the interactive elements should be of a large enough size to allow for less precise motor control [47].

The multitouch control method popular on market-leading touchscreen devices has the potential to allow for easier and more engaging interactions for people with dementia [41]. However, with multitouch, there is the risk of accidental gestures caused by users resting their hand on one part of the screen while interacting with another [17,56], although considered programming can prevent this [17,41]. Using familiar imagery to cue users into their activity can be helpful for people with cognitive impairment [54], and offering activities that are familiar to people, such as virtual representations of everyday environments to explore [53] or digital versions of existing games to play [10] has also shown to be popular with this population.

To support the design process, Astell et al [33] recommended educating all members of the research and development team on dementia and enabling everyone to spend time talking with people with dementia and seeking their input. An iterative design process in collaboration with users is also recommended [32,53]. This can reduce the risk of releasing products that have poor performance, stability issues, or are not fit for purpose, which is highlighted as being crucial in order to achieve acceptance and adoption by people with dementia, their families, and services supporting them [44].

Discussion

Application of Knowledge

Although the use of touchscreen technology with people with dementia is in its infancy across the board, of the 3 main contexts (assessment, ADL, and leisure) highlighted in the results, the most apparent gap in the literature is in the application of these devices for leisure activities. Only 8 articles were returned from the literature search that could be categorized in this area, and within these only 6 projects are featured, as multiple articles focused on the same work. This is all the more unusual given that worldwide the most popular app category in the market leading app store for smartphones and tablets is games. There is no reason to believe that a diagnosis of dementia should alter people's interests and hobbies. Moreover, one of the biggest challenges for people with dementia and those who care for them is finding ways to provide stimulating and meaningful activities for them to engage with.

Understanding why touchscreen technology has been used with this population in the past can help when making decisions as to how it might be used in the future. This is particularly pertinent, given the speed with which this technology evolves, and the availability of new design features both internally (software) and externally (hardware). Having reviewed the literature, clearly what has attracted researchers, clinicians, and designers working with people with dementia to touchscreen technology is the intuitive control method. While not entirely a new technology (Carr and colleagues were heralding its use 30 years ago [17]), its increase in availability, popularity and affordability in recent years has perhaps provided a new entrance into personal computing for people with dementia. The practicalities, customization and multifunctional abilities discussed in the literature could to a certain extent also be applied to non-touchscreen computing devices. However, in combination with the intuitive control method, it is no surprise that this technology is gaining the interest of those working with people with dementia. Areas that might require further consideration include how customization can best be implemented to improve the accessibility of this technology and how, with such large numbers of apps available, to identify which ones might be suitable for people with dementia.

Perhaps the most difficult outcome to analyze relates to the hardware, as there is a potential disparity between what is most available and popular on the market (and therefore presents the most opportunity) and what might be the most appropriate for this population. The majority of studies featured in this review used larger touchscreen devices (20˝ being the most common). In comparison with the Apple iPad, which was the single most used device in the remaining studies, this is almost 4 times the size. It is likely that in some of these cases there was no choice to be made as tablet devices with "acceptable" hardware have only been widely available since 2010 [58]. Given the knowledge gained on software design, a larger sized interface would certainly be beneficial for this population. However, with tablet devices like the iPad offering so many easily accessible, low-cost applications, and their smaller size (comparatively) offering more portability, there are advantages to this technology too. There is perhaps not enough information currently to definitively answer this question, and it is unlikely that there will be a "one-size-fits-all" solution, given the variety of contexts and individual variations (eg, individual or group activity, age, presence of physical impairment). If the principles of interaction derived from the earlier studies featuring larger touchscreens could be achieved with tablets, then this might

provide an accessible, economically viable approach going forward. It would also be sensible to consider the specific target population and context in advance of each study and consult with people with dementia and people in a caregiving role before making a decision.

Limitations

It became apparent during the review that many articles did not report all the information that might be considered pertinent to the completion of a comprehensive overview of this topic. This lack, combined with the relatively modest number of articles identified, is a limiting factor in applying the findings. For example, if the studies that reported trials of apps or devices consistently included information about the age and severity of cognitive impairment experienced by people with dementia, this would advance the knowledge about how the technology could be used at various stages of the condition. This is not to assume that there would necessarily be a correlation, for as Kerssens et al [9] reported, independent use was related more to personal motivation or curiosity for the technology than the level of cognitive function.

Another potential limitation is that the review may not have uncovered all studies that involved the use of touchscreen technology with people with dementia. The decision was made to include only articles that directly referred to the use of a "touchscreen" (or "touch screen") interface. Every effort was made to investigate alternative terminology but nothing consistent was found, therefore the presence of the term "touchscreen" (or "touch screen") dictated the search results. It also highlights the small amount of direct research touchscreens have received with this population beyond being an alternative to pen-and-paper cognitive tests.

Conclusions

The reviewed literature can be seen as an emerging body of evidence that people who have dementia can independently use touchscreen technology. Certainly, there are caveats here involving the appropriate level of support needed, both on a human and on a technological level, but there is clearly enough reason to warrant continued research in this area. The results have highlighted numerous learning outcomes while also identifying areas that are currently under-researched. It is clear that touchscreen devices are not only usable by people with dementia, but the wide array of functions available offer great potential to improve their lives in many different contexts.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Summarized literature review results.

[PDF File (Adobe PDF File), 56KB - rehab_v3i2e10_app1.pdf]

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Abbreviations

ADL: activities of daily living
LIM: Living In the Moment
NFC: near-field communication
OS: operating system

Original Paper

Teleexercise for Persons With Spinal Cord Injury: A Mixed-Methods Feasibility Case Series

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Abstract

Background: Spinal cord injury (SCI) results in significant loss of function below the level of injury, often leading to restricted participation in community exercise programs. To overcome commonly experienced barriers to these programs, innovations in technology hold promise for remotely delivering safe and effective bouts of exercise in the home.

Objective: To test the feasibility of a remotely delivered home exercise program for individuals with SCI as determined by (1) implementation of the intervention in the home; (2) exploration of the potential intervention effects on aerobic fitness, physical activity behavior, and subjective well-being; and (3) acceptability of the program through participant self-report.

Methods: Four adults with SCI (mean age 43.5 [SD 5.3] years; 3 males, 1 female; postinjury 25.8 [SD 4.3] years) completed a mixed-methods sequential design with two phases: an 8-week intervention followed by a 3-week nonintervention period. The intervention was a remotely delivered aerobic exercise training program (30-45 minutes, 3 times per week). Instrumentation included an upper body ergometer, tablet, physiological monitor, and custom application that delivered video feed to a remote trainer and monitored and recorded exercise data in real time. Implementation outcomes included adherence, rescheduled sessions, minutes of moderate exercise, and successful recording of exercise data. Pre/post-outcomes included aerobic capacity (VO_2 peak), the Physical Activity Scale for Individuals with Physical Disabilities (PASIPD), the Satisfaction with Life Scale (SWLS), and the Quality of Life Index modified for spinal cord injury (QLI-SCI). Acceptability was determined by participant perceptions of the program features and impact, assessed via qualitative interview at the end of the nonintervention phase.

Results: Participants completed all 24 intervention sessions with 100% adherence. Out of 96 scheduled training sessions for the four participants, only 8 (8%) were makeup sessions. The teleexercise system successfully recorded 85% of all exercise data. The exercise program was well tolerated by all participants. All participants described positive outcomes as a result of the intervention and stated that teleexercise circumvented commonly reported barriers to exercise participation. There were no reported adverse events and no dropouts.

Conclusion: A teleexercise system can be a safe and feasible option to deliver home-based exercise for persons with SCI. Participants responded favorably to the intervention and valued teleexercise for its ability to overcome common barriers to exercise. Study results are promising but warrant further investigation in a larger sample.

KEYWORDS

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Introduction

In the United States, approximately 300,000 adults are currently living with a spinal cord injury (SCI) [1], and 50% of them report performing little to no physical activity other than their activities of daily living [2]. Those who report being physically active only engage in approximately 27 minutes of activity per week [3], a level substantially lower than the minimum recommended national guidelines for able-bodied adults [4] and recommendations made specifically for persons with SCI [5]. Because only a small percentage of persons with SCI are able to meet the national physical activity guidelines of 150 minutes per week of moderate aerobic exercise, it is not surprising that poor metabolic [6] and cardiovascular health [7] is often observed in this population. Additionally, those who are chronically inactive are at risk for secondary conditions including pressure ulcers, infections, and depression, which may even reduce life expectancy [8]. Such complications and deconditioning are preventable and often reversible by long-term, regular engagement in exercise. Unfortunately, persons with SCI have numerous barriers to exercise impeding their likelihood of adopting a consistent exercise routine [9].

The most commonly reported barriers to exercise by persons with SCI include both intrapersonal issues (eg, lack of energy, motivation, or knowledge) and those related to the built or organizational environment (eg, lack of accessible or affordable fitness facilities, equipment, and/or knowledgeable staff) [9-11]. In an effort to assist individuals in overcoming these barriers, recent innovations allow health care providers to deliver services to people in their homes through communication technologies (eg, smartphone or live video feed through the Internet), referred to as telehealth. Advantages of telehealth over usual care include greater cost-effectiveness, increased social support and access, better care, and higher quality of life [12]. With regard to individuals with SCI, telehealth has been proven to help in the management of pressure ulcers [13] and implementation of other strategies to promote healthy behaviors [14]. However, less is known about the potential of telehealth interventions that offer remotely delivered exercise training, a subset of telehealth called teleexercise.

Conceivably, persons with SCI could overcome both intrapersonal and environmental barriers through teleexercise. Technology can provide them with real-time monitoring of physiological data (eg, heart rate, respiratory rate) with instructions via live video feed from a remote fitness expert, enabling them to receive motivational support and potentially more accurate, safe, and effective doses of exercise. Thus, monitored teleexercise holds promise as a method of intervention that can address many of the most commonly reported barriers to exercise. To address the question of whether a monitored Web-based exercise intervention is feasible for individuals with SCI, this study assessed three core areas of feasibility [15] through the following aims: (1) test the implementation of delivering the intervention successfully at the home; (2) explore the potential effects of the intervention on aerobic fitness, physical activity, behavior, and subjective well-being; and (3) assess the acceptability of the program through participant self-report.

Methods

Study Design and Participants

A convenience sample of four middle-aged adults (mean age 43.5 [SD 5.3] years; 3 males, 1 female; postinjury 25.8 [SD 4.3] years) with chronic SCI was recruited for a 2-phase (sequential) mixed-methods design [16] (Figure 1). Participant characteristics are shown in Table 1. The first phase, the intervention, consisted of 8 weeks of aerobic exercise with quantitative data collected pre- and postintervention. During the second phase, the intervention was withdrawn, and participants were instructed to resume their normal daily activities for 3 weeks. Participants were interviewed at the end of this period to qualitatively explore their perceptions of the program's features and impact on their daily routine after completion. The arbitrary sample size of four was chosen to determine if the study could be administered as intended.

Table 1. Participant characteristics.

Participant	Age (years)	Sex	BMI[a] (kg/m^2)	Lesion level[b]	Years post injury
1	43	Female	19.5	T1[c]-T2	25
2	50	Male	27.1	T10-T11	28
3	44	Male	42.7	C4[d]-C5	30
4	37	Male	26.1	T2-T3	20

[a]BMI: body mass index.

[b]Lesion level: spinal cord injury level.

[c]T: thoracic.

[d]C: cervical.

Participants were eligible for inclusion in this study if they were aged 19 to 65 years and diagnosed with an SCI, used a wheelchair as their primary means of mobility, reported being physically inactive for 6 months prior to recruitment (no participation in a structured exercise program), were able to independently operate an arm ergometer; and had access to a wireless Internet connection. Participants were excluded if any known orthopedic, vascular, or cardiac problem interfered with the study protocol. This protocol was approved by the university's institutional review board.

After participants provided written informed consent to the study protocol, they were instructed to come to the laboratory for pre- and postintervention data collection (week 0 and 9).

During these visits, participant aerobic capacity (VO$_2$ peak), quality of life, self-reported physical activity, satisfaction with life, and demographics were recorded.

Figure 1. Study design and timeline: mixed-methods sequential design.
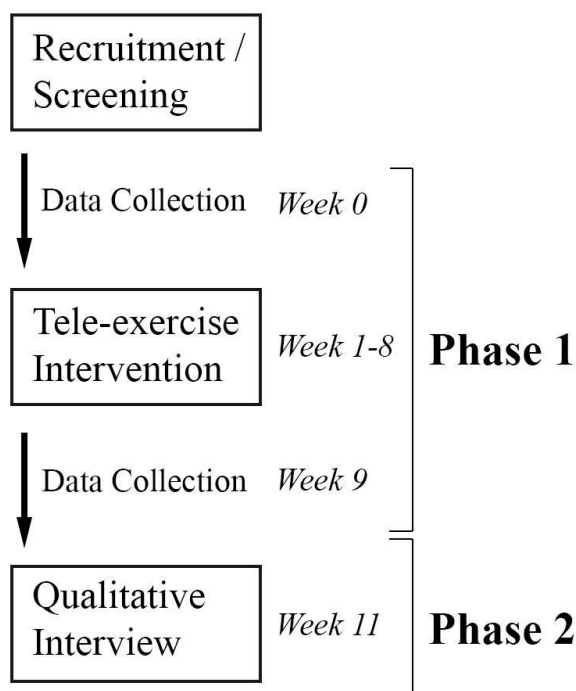
Intervention

Instrumentation

The teleexercise intervention was delivered through a custom, wireless Internet-based system installed in the participant's home. The equipment in this system included a tablet computer (Samsung Galaxy Tab 2 10.1, Samsung) with Bluetooth and wireless Internet capability mounted to an adjustable floor stand (Standzfree Universal Stand, Standzout); wearable physiologic monitor (Bioharness 3, Zephyr) that provided real-time monitoring of heart and respiration rate data to the tablet via Bluetooth connection; and custom-designed Web application that allowed physiologic data to be recorded from the tablet to a secure Web-based dedicated server. An example of this setup is shown in Figure 2. This platform allowed the exercise trainer (telecoach) to monitor each participant's physiologic data in real time (up to 5-second delay) while simultaneously videoconferencing and providing written instructions to the participant. Written instructions served as an outline for daily and weekly exercise goals, which complemented verbal instructions given to the participant during the exercise session. For example, when asking participants to report their exertion

level, telecoaches could provide a visual representation of a rating of perceived exertion (RPE) scale. The Web-based platform from the telecoach and participant perspective is shown in Figure 3. Telecoaches utilized this system to provide immediate feedback regarding exercise intensity and movement quality during each session. All exercise sessions were performed on an upper body ergometer (UBE-BDP Table Top Upperbody Exerciser, Hudson Fitness).

This study was designed to protect privacy and used state-of-the-art Internet data security mechanisms. First, no identifiable personal information was monitored or recorded through the teleexercise system. All personal information was stored separately on paper, and only the principal investigator had access. Second, the teleexercise system transferred all data, including physiologic and audiovisual communication, over a secured channel utilizing state-of-the-art encryption software. Physiological records were transferred to the remote server over HTTPS protocol based on 256-bit advanced encryption standard with cipher block chaining. Audiovisual communication between trainer and participant utilized WebRTC technology, based on peer-to-peer communication over Datagram Transport Layer Security protocol.

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Figure 2. Equipment used in the intervention and a demonstration of the setup in the home.

Figure 3. Exercise session from the telecoach's view (top) through online access to the dedicated server and the participant's view (bottom) from the custom-designed Web application.
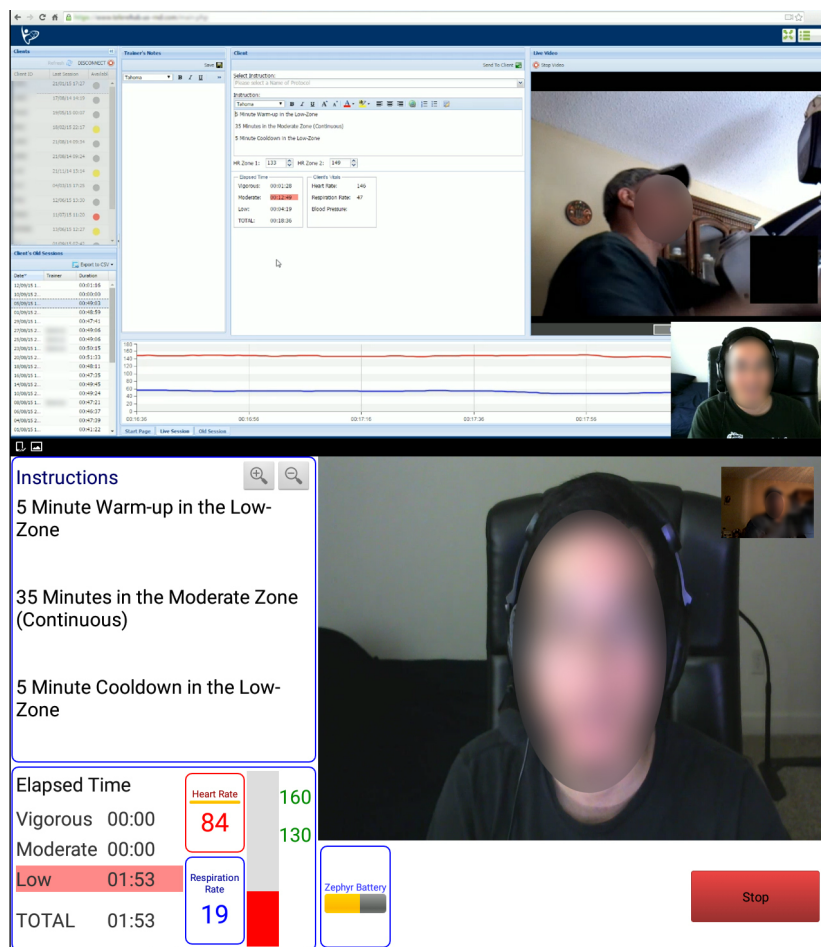
Intervention Protocol

The teleexercise intervention was delivered 3 times per week for 8 weeks (24 sessions). Sessions were separated by a minimum of 24 hours. Utilizing the teleexercise system, the training was delivered to the participants in their homes remotely by telecoaches located at the university research laboratory. To instruct and familiarize participants with the system, telecoaches conducted the first exercise session with each participant in the home after setting up the equipment. Additionally, telecoaches

used this time to establish the regular exercise schedule with participants. Participants were allowed to choose the days and times they felt the exercise sessions would best fit their schedule. In the event participants could not attend or needed to reschedule an exercise session, they were informed to contact their telecoach via telephone. Participants were instructed to choose the day and time of the rescheduled session to avoid the telecoach influencing this variable. Lastly, they were told to report any injury or adverse event they experienced throughout the program to their telecoach.

During each exercise session, participants were instructed to maintain moderate exercise intensity, approximately 60% of their heart rate reserve (HRR) [17], using real-time heart rate data and collected RPE. The duration of each exercise session gradually progressed over the course of the 8 weeks with a goal of reaching 30 minutes of exercise (90 minutes total) at a moderate intensity by the fourth week of intervention. The 30 minute, 3 times-per-week exercise prescription was chosen to reflect the upper tier of aerobic exercise prescriptions commonly used in research for SCI [5,18]. The 4-week time frame was chosen based on a pilot test conducted prior to this study. At the start of the intervention, telecoaches set the goal of moderate exercise performed per session at a level that participants felt was comfortable. Each session included both a 5-minute warm-up and cool-down. Telecoaches then instructed participants to increase the duration of exercise when a participant could perform the moderate exercise minutes in two consecutive sessions and/or reported less than a moderate RPE (less than 3 on the modified Borg RPE 0-10 scale) [19] during moderate intensity exercise (indicated by heart rate data). Trainers encouraged participants to gradually increase duration of moderate exercise in increments of 5 to 10 minutes.

Telecoaches provided social support and assisted participants in maintaining moderate exercise intensity throughout the intervention. If a participant's heart rate was too low during an exercise bout, telecoaches provided encouragement to increase the performed workload by either pedaling faster or increasing the resistance. Likewise, telecoaches strongly encouraged participants to lower their pace or resistance if participants exceeded the prescribed heart rate training zone. Telecoaches also monitored respiration rate for abnormalities in breathing. To avoid shoulder injury due to overuse, telecoaches instructed participants to alternate between forward and backward pedaling if severe muscle soreness occurred. Telecoaches prompted participants on a weekly basis to report any signs of injury or adverse events. To support the telecoach verbal instructions, exercise goals for each session (eg, a specific heart rate for a given amount of time) were provided in real-time written messages through the teleexercise platform. These messages provided participants with visual goals for the exercise session as a point of reference and an alternate means of communication in the case of audiovisual Internet lag. Lastly, telecoaches answered exercise-related questions raised by participants, but refrained from answering questions related to other lifestyle behaviors such as nutrition and diet.

Outcome Measures

Implementation Outcomes

To assess the extent to which teleexercise can be successfully delivered in the home for persons with SCI, quantitative data including adherence, exercise session records, adverse events, and minutes of moderate exercise each week were recorded throughout the intervention.

Adherence to the intervention was defined as the percentage of total exercise sessions attended including rescheduled sessions. To be classified as a reschedule, the exercise session had to be performed before the next regularly scheduled session. If sessions were allocated to a later date past the next normally scheduled session, they were counted as a missed session (nonadherence). Based on previous studies [20], researchers considered 75% attendance to be considered acceptable.

To assess the stability of the monitoring technology of the Internet-based system, exercise recordings were assessed throughout the intervention. Successful exercise recordings were defined as the percentage of sessions that were monitored, recorded, and stored to a secure dedicated server over the Internet through the teleexercise Web application. A successful exercise recording required all data within these sessions to be saved successfully, including heart rate, respiration rate, and minutes of exercise. No published criteria for an acceptable percentage of exercise records have been established for this outcome.

Minutes of moderate exercise performed were recorded to evaluate the suitability of the intervention exercise prescription (ie, intensity and duration). Since the progression of the exercise prescription was exploratory in nature, no specific feasibility criteria were determined a priori. However, trainers aimed to guide participants toward the goal of 90 minutes of moderate exercise by the fourth intervention week. For exercise sessions where data were not able to be recorded through the teleexercise system due to technical difficulties (eg, Internet disconnection/disruption or equipment errors), minutes of moderate exercise were averaged for the remaining two exercise sessions performed that week.

Quantitative Outcome Measures

To provide future studies with an estimate of outcome variability for common health-related measures, quantitative outcomes included aerobic capacity and a set of health-related questionnaires that assessed the impact of the intervention on participant daily lifestyles.

Arm ergometers are generally held as an effective mode of aerobic exercise for persons with SCI [5,18]. Thus, peak oxygen consumption (VO_2 peak, ml·kg^{-1}·min^{-1}), a gold-standard measurement of aerobic capacity, was assessed during a graded exercise test on an upper body ergometer. Prior to starting the test, participants were given a 3-minute rest period. Participants were instructed to maintain a pedaling cadence of 60 revolutions per minute while resistance was increased every minute by 10 watts until the participant reached volitional fatigue or achieved 3 of 5 criteria: age predicted heart rate max of more than 85%; RPE of 17 or more; respiratory energy exchange ratio of 1.1 or higher; plateau in oxygen consumption; or volitional fatigue [21]. Heart rate and oxygen consumption were recorded continuously during rest and exercise. Metabolic measures were taken using open circuit spirometry with a metabolic cart (TruOne, ParvoMedics). As a safety precaution, blood pressure was recorded before and after the exercise test. VO_2 peak values reported for untrained male and female adults (young and middle-aged) with SCI (paraplegia) are defined as poor (less than 12 ml·kg^{-1}·min^{-1}), fair (12-15.3 ml·kg^{-1}·min^{-1}), average (15.3-17.7 ml·kg^{-1}·min^{-1}), good (17.7 -22.4 ml·kg^{-1}·min^{-1}), and excellent (more than 22.4 ml·kg^{-1}·min^{-1}) [22].

Since quality of life is closely linked to independent living, it has been identified as a critical outcome for therapeutic exercise [23]. In this study, quality of life was assessed by the Quality of Life Index [24] modified for SCI [25,26]. The QLI-SCI consists of 37 questions that assess importance and satisfaction with various aspects of life and utilizes a 6-point Likert scale from least satisfied/important to most satisfied/important. Questions are divided into 5 subscales: total quality of life, health and functioning, social and economic, psychological, and family. Scores from each subscale were combined into a total score using equations provided by the authors [27], with higher values representing a greater perceived quality of life. The general QLI has demonstrated excellent internal consistency (Cronbach alpha = .93) and test-retest reliability (r=0.87) and good validity with generic life satisfaction [24].

As an additional measure of subjective well-being , satisfaction with life was recorded using the Satisfaction with Life Scale (SWLS) [28]. The SWLS is a brief 5-question survey that utilizes a 7-point Likert scale from strongly disagree to strongly agree with scores ranging from 5 to 35. The SWLS has demonstrated good internal consistency (Cronbach alpha = .83) in persons with SCI [29] and good validity with other measures of well-being [30]. Higher scores indicate a greater degree of life satisfaction. Satisfaction with life has been identified as a common construct of well-being examined in exercise literature conducted for persons with SCI, with some evidence to suggest that it is positively affected by exercise [31].

To assess the influence of the exercise intervention on daily physical activity, physical activity was assessed using the Physical Activity Scale for Individuals with Physical Disabilities (PASIPD) recall questionnaire [32]. The PASIPD includes 13 questions related to the performance of activities of daily living over a 7-day period. End scores are converted into metabolic equivalents (MET hours/week). Scores can range from 0 (inactive) to more than 100 (very high activity). This instrument has demonstrated reliability and validity in a sample of persons with mobility impairment that included individuals with SCI [32,33].

Acceptability Outcomes (Qualitative)

Acceptability of the program was assessed qualitatively via participant self-report after program completion. Employing qualitative investigation in this manner has been suggested to enhance the overall content and depth of information provided by feasibility studies [34]. At week 11, 3 weeks after completion of the 8-week intervention, participants were interviewed. This time period was chosen to explore the possible impact of the intervention on participants' daily routines and avoid reporting bias (social responsiveness), where participants provide answers at study completion they feel are in accordance with the expectations of the study or researchers, particularly when researchers view their outcomes [35]. The interview was semistructured, consisting of one ice-breaker question and 9 open-ended questions. These questions aimed to obtain participant feedback about the delivery of the teleexercise program, identify perceived advantages and disadvantages of the program, describe how their teleexercise experience might compare to a typical fitness facility, evaluate how the program

affected their adherence, and explore the overall impact of the intervention from the pre-exercise baseline to the end of the 3-week follow-up period. An example of the interview questions and guide is provided in Multimedia Appendix 1. Participant interview data were recorded via audio devices and transcribed verbatim. Participants were given pseudonyms to ensure confidentiality of reported data. Interviews were conducted in a setting chosen by the participant (eg, the university research laboratory, their home).

Analysis

Quantitative

Adherence was reported as a percentage of the prescribed exercise sessions attended during the intervention. VO_2 peak and questionnaire data (quality of life, satisfaction with life, and 7-day physical activity recall) were reported at pre- and post-exercise intervention.

Qualitative

Two researchers analyzed qualitative data descriptively. The constant comparative method [36] was used to code emergent themes/categories from participant qualitative interview data. Within the constant comparative method, themes were coded and compared as they were collected for each participant. Within each participant's interview data, events that emerged were first coded into initial categories or themes. After initial coding was completed, the emergent theoretical categories and their properties were reduced into fewer, more universal themes. The resultant major themes were reported. No statistical software was used. In the context of coding, analysts operated inductively within a post-positivism paradigm. In accordance with our objectives, this viewpoint was taken to focus coding on the participant perspectives and experiences, as opposed to a heavy interactive influence of the trainer (constructivist paradigm) [37]. Data were coded openly: no pre-existing criteria or themes were held.

Measures were taken to enhance the credibility and validation of the qualitative methodology. All interview data were transcribed by staff not involved with data analysis and reporting to prevent researchers from influencing the results to portray a certain outcome by recreating text, for example (experimenter bias). Additionally, qualitative data were checked by participants for accuracy (member checking) in two forms: (1) researchers asked participants to clarify ambiguous interview data and (2) themed data were cross-checked by participants for accuracy. Coding was first performed individually and then reviewed collectively by the lead investigator and a third-party reviewer, a method referred to as triangulation [38]. After individual codings were compared, researchers discussed their disagreements to resolve as many discrepencies as possible. This method, referred to as negotiated agreement [39], was employed to narrow the large variety of codes that could potentially be identified from open coding. Finally, for simplicity, interrater agreement among researchers was expressed as a proportionate percentage for major and minor themes [40]. The third-party reviewer had a background in qualitative research and had no direct involvement with the intervention, resulting in less intervention bias. The primary

interviewer had a background in adapted physical activity and was a telecoach for the majority of the teleexercise sessions.

Results

Implementation Results

All four adults completed the intervention and were included in the final data analysis. Participants attended all 24 exercise sessions (100% adherence) with 8 of the total 96 sessions (8%) classified as reschedules. Reasons for rescheduled sessions included work-related conflicts (n=2), errands (n=2) out of town (n=1), Internet service provider issues (n=1), family obligations (n=1), and not feeling well (n=1).

Exercise sessions were successfully recorded to the dedicated server for 82 of the 96 sessions (85%) performed by the four participants. The primary causal factors for the 14 unsuccessfully recorded sessions were Internet connection/stability issues (9 occurrences) and irregularities in saved heart rate data (5 occurrences). One participant lived in an urban area and the other three participants lived in rural areas.

Data were recorded in real time by the teleexercise system and categorized into either light/rest, moderate, or vigorous intensity exercise. Data for the four participants showed total minutes of exercise performed each week increased throughout the 8-week intervention (74.1 [SD 26.3] minutes at week 1 to 137.5 [SD 11.1] minutes at week 8). Participants appeared to plateau in the amount of moderate exercise minutes they achieved halfway through the intervention. Minutes of moderate aerobic exercise performed each intervention week are shown in Figure 4. At the start of the intervention (week 1) participants performed an average of 24.3 [SD 10.5] minutes of moderate exercise. At week 4, they achieved 74.8 [SD 37.8] minutes. At week 8, they held 76.5 [SD 29.7] minutes.

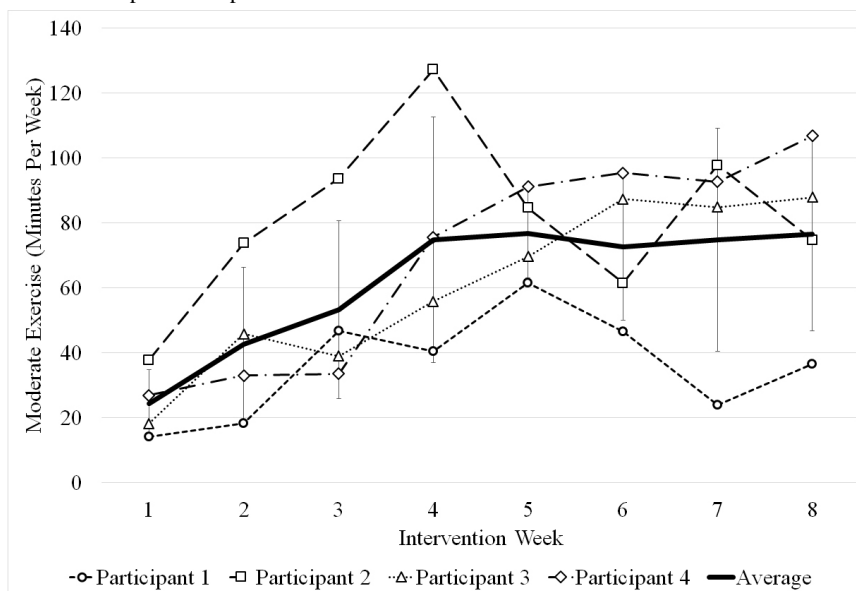**Figure 4.** Minutes of moderate exercise performed per week.

Table 2. Quality of Life Index: Spinal Cord Injury Version results.

Participant	Total score pre	Total score post	Health & function[a] pre	Health & function post	Social & econ[b] pre	Social & econ post	Psych[c]/spirit[d] pre	Psych/spirit post	Fam[e] pre	Fam post
1	23.5	22.2	24.1	23.7	23.1	22.6	21.7	21.7	24.3	19.2
2	17.1	18.5	13.9	16.9	20.1	20.2	23.8	22.6	10.9	10.3
3	18.5	22.0	17.8	21.7	18.1	23.3	18.6	23.5	19.1	17.9
4	22.7	20.7	23.4	21.1	22.9	20.4	22.7	21.4	18.0	16.6
Mean (SD)	20.5 (3.1)	20.9 (1.7)	19.8 (4.8)	20.9 (2.9)	21.1 (2.4)	21.6 (1.6)	21.7 (2.2)	22.3 (1.0)	18.1 (5.5)	16.0 (4.0)

[a]Functioning.

[b]Economic.

[c]Psychological.

[d]Spiritual.

[e]Family.

Quantitative Outcome Measure Results

Information for aerobic capacity, satisfaction with life, and physical activity data for each participant from pre- to post-data collection are shown in Figure 5. Responses varied among participants. The intervention appeared to have no impact on quantifiable outcomes for participant 1, who achieved the lowest amount of moderate exercise. Participants 2, 3, and 4 achieved a similar amount of moderate exercise and showed increases in VO_2 peak values (ranging from 0.7 (18%) to 4.9 (39%) $ml \cdot kg^{-1} \cdot min^{-1}$) and daily physical activity (ranging from 4.13 to 19.3 MET hours per week), which likely implies the existence of a dose-training effect.

The two participants with the lowest aerobic capacity at the start of the study had the highest increases in daily activity and certain aspects of subjective well-being upon study completion. Participants 2 and 3, who reported the lowest MET hours per week and VO_2 peak values at pre-data collection, showed increases of 10.3 and 19.3 MET hours per week, respectively. Additionally, they showed a 77% (from 18 to 31) and 27% (from 22 to 28) increase in SWLS scores, respectively. Likewise, in regard to quality of life, they showed increased scores in the health and function subcategory of the QLI-SCI (participant 2: pre=13.9, post=16.9; participant 3: pre=17.8, post=21.7). However, there did not appear to be any consistent notable differences overall in total or subscale scores on the QLI-SCI as shown in Table 2.

Figure 5. Peak oxygen consumption pre- and postintervention by participant; Satisfaction with Life Survey (SWLS) scores; reported physical activity performed over the past seven days (PASIPD).
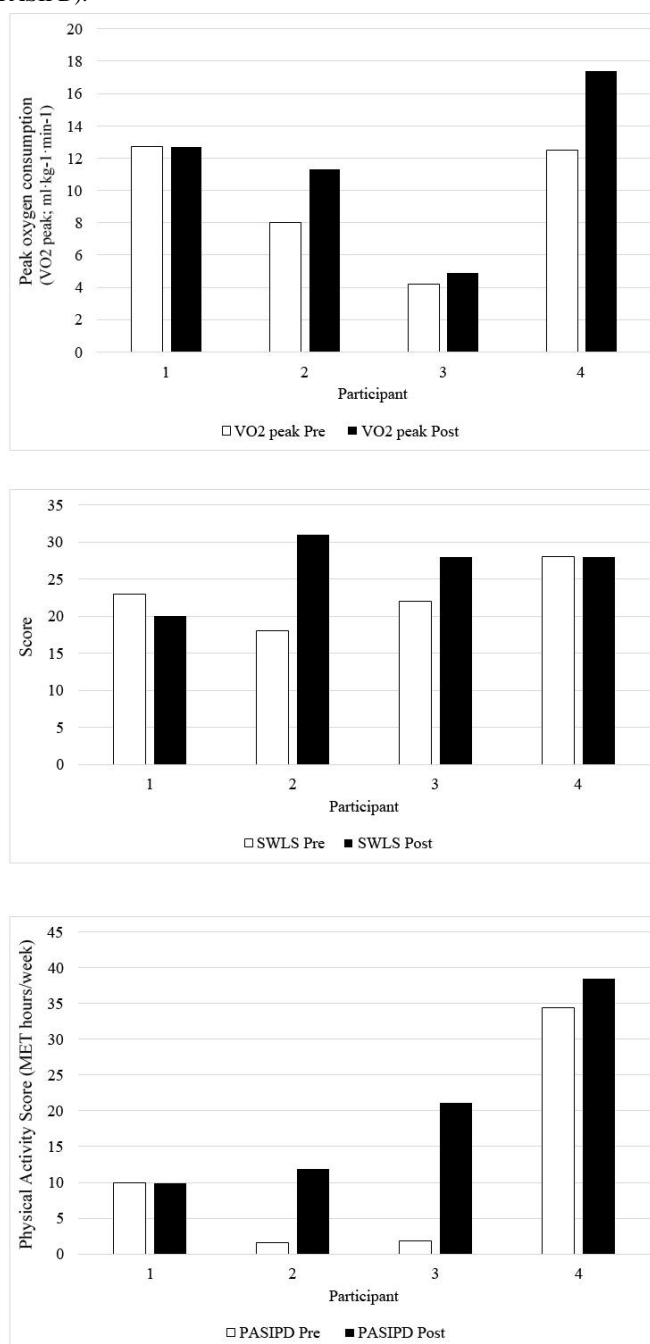
Acceptability Results

Five major themes emerged from the qualitative interview data: (1) barriers to exercise at typical fitness facilities; (2) teleexercise as a solution to exercise barriers, (3) positive outcomes associated with teleexercise, (4) importance of the telecoach as a motivator, and (5) suitability of the employed teleexercise technology. Transcripts were independently coded by two researchers to ascertain emergent themes. Once transcripts were coded, the researchers met to discuss the analysis; interrater coder agreement was 100%.

Barriers to Exercise at Local Fitness Facilities

Participants identified numerous barriers to exercise at their local community fitness centers, including lack of access, convenience/time, usable equipment/program options, transportation, staff expertise in the area of disability, and high cost. Lack of transportation and convenience/time were noted by all four participants; access, usable equipment/program options, and staff expertise were identified by three participants.

> *I went to the gym. . . It's probably not but five miles from the house. But there's no accessible parking because they don't expect people in wheelchairs to show up. And then I have to get into the gym itself. But then when you get into the door, there's no way to even get around. I can go maybe ten or fifteen feet to get to some of the machines. . . I can't even use them because their benches don't come loose. . .* [Participant 3]

Teleexercise As a Solution to Exercise Barriers

Participants expressed a preference for teleexercise because they felt it provided a solution to exercise barriers, particularly those related to the environment. Specifically, all four participants acknowledged teleexercise as a convenient solution to exercise at a typical fitness facility. For example, participant 4 was employed full-time and also performed chores around his residence immediately upon arriving home from work. This participant performed his exercise sessions with a telecoach at 9 pm, a task he felt too difficult to do with an exercise trainer at a typical fitness facility which would require time allotted for transportation, transferring in and out of a wheelchair, and changing clothes. This participant successfully completed all 24 exercise sessions with only three of those sessions needing to be rescheduled.

> *I did it [teleexercise] more because it's more convenient and on my time. You know I don't have to make time to go there, get out of the truck, go in, and come back. You know you kill an hour easy. . . Well an hour and a half if you figure the time it takes to get out and go in, you know, get on your machine.* [Participant 4]

Three out of four participants identified teleexercise as an accessible and usable option versus going to a fitness facility.

> *A typical gym doesn't even have the facilities for me to get a lot of the exercise machines. . . I could use free weights . . . but most of the machines were not adapted enough for me to use. . . There wasn't really anything that I was doing that was aerobic.* [Participant 2]

> *It's a step that I see as needed [teleexercise] because, as a quad, it is very hard to find exercise programs. I mean, the last exercise program that I had was in therapy while I was in the hospital as an inpatient. You don't get the regimen of exercise as a quad because most gyms aren't even slightly accessible.* [Participant 3]

Positive Outcomes Associated With Teleexercise

All four participants made several positive comments associated with the teleexercise program. These included increased energy/endurance and strength. They reported that these improvements increased their ability to perform physical activity. Additionally, three out of four participants mentioned that their increased physical capacity led to increased frequency and duration of physical activity and various occupations (meaningful, purposeful, and enjoyable forms of activity) after completing the intervention.

> *I think I'm 40% more active now since I've done it. . . I have a little more energy to go to the park. . . So, coming to the park and actually getting out and strolling around the park. . . I guess it has really gotten me out more.* [Participant 1]

The most impressive improvements in activity behavior were reported by those with the lowest physical capacity.

> *Before I would be up for about an hour, eat a meal, and then go to bed. This allowed me to stay up and interact and be a part of the family gathering. This was a really good side-effect of the program in that it built me up so I could stay up longer. . . I was stronger, had more mobility.* [Participant 2]

> *I can do what I did before (the intervention) but a lot more efficiently physically. So, I can get stuff done. Some things I can do faster. Some things I can do and still have energy. I can stay up and stay out longer. . . My days are 16 to 18 hours in the chair. Where I was at before was like 12 hours.* [Participant 3]

Participant 3 also described a noteworthy improvement in the amount of time spent participating in his physical activity/occupation. Participation in his weekly hobby, remote-controlled car racing within a community club, was impeded by a lack of energy prior to the intervention. The duration spent participating in his hobby with his friends increased from 1 to 2 hours to 4 to 7 hours after the intervention. He emphasized that this improvement enhanced his motivation to adhere to the teleexercise program.

> *I noticed after exercise that I could drive my car longer. Driving the car for me requires a lot of shoulder work because I have to hold my hands still while I'm controlling the car. . . Before the intervention I could race for ten to fifteen minutes then I'd have to take a break. But after the intervention, I could do it for an hour or two.* [Participant 3]

Participants 2 and 3 also reported sustained exercise behavior throughout the 3-week follow-up period after the intervention. During this period, both participants maintained and built upon the frequency and duration of their previous exercise regimens using arm cycles, which they had purchased via the Internet soon after the intervention was completed.

Telecoach As a Motivator

Participants appreciated the motivation and expertise that telecoaches provided through the teleexercise system. All four participants acknowledged the telecoaches as the primary facilitator of their motivation to adhere to the program. They acknowledged that the trainer provided monitoring, feedback, a social presence and bond, and gave them a sense of accountability to attend the exercise sessions.

> I think it's something that's really useful as far as motivation. . . Having somebody checking in on me and asking about what I was doing and how I was doing. . . It made it go a lot faster in that you had somebody to talk to you while you were working out. . . I was accountable because someone was meeting with me. [Participant 2]

> Just having somebody there working out with you. You know that helps you, motivates you. Doing it by yourself you're not going to push yourself as hard. You've got somebody there with you you're gonna go harder, and plus it makes the time go by quicker when you're sitting there talking with them. [Participant 4]

Suitability of the Employed Teleexercise Technology

Participants acknowledged teleexercise technology as a feasible method for delivering exercise to a larger scale of persons with SCI but also noted several challenges. Three out of four participants identified issues with technology as a major disadvantage of teleexercise. One participant noted that the size of the tablet screen (10.5 inches) was challenging to read. Three participants noted Internet and tablet connectivity issues were interrupting and sometimes distracting with the exercise sessions.

> The only issue I can think of would be of course the bandwidth. Bandwidth is a problem because you have to have a pretty solid upload and download speed. [Participant 2]

In contrast, all four participants reported that the technology was easy to use.

> I was familiar with the equipment, but I don't think it was hard to use at all. Cause all you had to do was turn it on and click. [Participant 4]

Most importantly, all four participants felt that teleexercise was capable of reaching a larger population of persons with SCI.

> I just wish that more people that are. . . disabled, would participate in it. And it's helpful, you know it's like a starting point. . . For getting me up and out. You know, more active and motivated. [Participant 4]

Discussion

Principal Findings

Summary

This study explored the feasibility of delivering a remotely monitored aerobic exercise program at home for persons with SCI. Overall, acceptable rates of adherence and recording and monitoring of exercise data suggest successful implementation of core intervention components. Encouraging preliminary findings from quantitative data included increased aerobic capacity, level of physical activity, and satisfaction with life, but these responses varied. In terms of acceptability, participants responded favorably to the intervention. They described positive outcomes as a result of the intervention. Furthermore, they described it as advantageous for overcoming barriers to exercise typically experienced at a fitness facility and identified their relationship with a telecoach as a critical component of their motivation to exercise. Taken together, this intervention provides fitness professionals with a preliminary model for delivering supervised exercise services to persons with SCI at home. Online fitness trainers are becoming more and more available but to our knowledge, there are no online personal training programs for persons with SCI.

Implementation

In regard to implementation, researchers felt the intervention was administered as intended. This was primarily suggested by the high rate of intervention attendance (100% vs the feasibility indicator of 75%) and no reported adverse events. Though 8% of sessions were rescheduled, researchers felt this rate was acceptable based upon their clinical experience with supervised exercise training. Additionally, researchers felt that successfully recording 85% of all exercise data was satisfactory considering the unpredictable nature of Internet stability and that all variables (heart rate, respiratory rate, and minutes of exercise) were required to be classified as a successful recording.

Of the exercise sessions that were not recordable, Internet disconnection issues were the primary causal factor. Initially, we attributed these issues to the fact that the intervention was primarily delivered in rural locations with frequent inclement weather conditions (ie, heavy rain and wind), both of which can affect Internet stability. However, the amount of disconnects decreased as telecoaches and research staff gained experience with the system; 86% (12/14) of unsaved exercise sessions occurred in sessions performed by the first two participants. Simple configurations, such as resetting or relocating the Internet router, greatly enhanced Internet stability. Difficulties experienced with Internet connectivity were similar to those reported in the literature [41,42]. Remote monitoring technology should aim to provide opportunities for exercise data to be saved after Internet disconnection and resumed once connection is restored. Additionally, telecoaches and/or research staff should implement mock training sessions to enhance familiarity with trouble-shooting various problems that can occur with the use of Internet technology in a home setting.

The exercise prescription required a more gradual progression than anticipated. The majority of participants in the present

study were able to satisfy the minimum aerobic exercise guidelines for persons with SCI (40 minutes moderate exercise per week) [5], but they were far from reaching national aerobic exercise guidelines for adults established by the US Department of Health and Human Services [4] and the American College of Sports Medicine (150 minutes moderate exercise per week) [18]. Thus persons with SCI may require a longer progression of training to reach this target goal.

Potential Intervention Effects

Although our sample size limits statistical analyses, preliminary findings suggest the majority of participants experienced modest improvements in aerobic capacity and physical activity. Across the four participants, we observed a relative overall increase in aerobic capacity of 24%. As anticipated with exercise performed at a moderate intensity level [18], these gains are consistent to those reported by previous onsite aerobic interventions for SCI [43,44,45], and may also reflect increased satisfaction with life scores [46]. Quantitative findings appeared most prominent for those who performed a greater amount of moderate exercise or had lower starting values at the beginning of the study. In contrast, participant 1 (the only female) reported no improvements in quantitative data. It is unclear why some individuals respond more or less than others, which is the impetus for exercise dosing studies to inform more personalized exercise prescriptions. One potential explanation for this occurrence in participant 1 is that she performed a relatively lower weekly amount of moderate exercise compared to the other participants. In regard to quality of life, the duration of the current study was most likely too brief to achieve improvements observed in longer investigations [47]. Overall, these findings provide preliminary estimates of the variability of health-related exercise outcomes conducted for people with SCI. Further study is required to investigate these effects in a larger sample.

Acceptability

Participants provided positive feedback regarding physiological outcomes, the interaction with a telecoach, and the technology that was used in the teleexercise program. Although issues with Internet stability were described, all participants reported that the technology was easy to use. Participants noted that the technology removed several barriers to exercising at a local fitness facility, including not having to deal with inaccessible facilities and not demanding excessive amounts of time getting to and from the facility. These are common barriers to exercise for individuals with SCI [9-11]. Participants reported that the convenience of the program and the interaction with a telecoach contributed to their high adherence rates, suggesting that individuals with SCI can respond favorably to technology-based exercise programs at home.

Future Directions

Several opportunities exist to enhance the technology used in the present study. First, future studies that aim to employ teleexercise should consider incorporating additional devices to enhance connection stability. For example, wireless access points can enhance stability in situations where computer tablets are located at great distance from an Internet router. Likewise,

if Internet stability is the main concern, Ethernet adapters for computer tablets can allow direct Internet connection to a router and bypass issues with wireless Internet interference. In addition, future studies may benefit from incorporating innovative devices to enhance the visual clarity or overall user experience. One participant noted that the 10-inch screen tablet was challenging to read. Larger computer tablets or projection of data through digital cameras to larger digital screens, such as Smart TVs or computer monitors, may address this issue. Furthermore, trainers and research staff noticed participants often required assistance from a spouse/family member to equip heart rate monitors around their chest. Advances in wrist or upper arm heart rate monitoring technology will likely enhance the independence of teleexercise programs.

Qualitative findings indicate that one of the key benefits of the program as described by all participants was an increased physical capacity. These benefits allowed participants to engage in more healthy behaviors, particularly for those with lower baseline scores on physical capacity. It is unclear whether these benefits would be sustained over a longer time frame. Future studies that include the application of behavior change theories specific to physical activity are necessary to validate these findings. Specifically, these studies should examine strategies that can retain behavior over the long term (ie, 6 months to 1 year).

All participants valued the motivation and disability-related expertise provided by the telecoach, which they reported as a primary facilitator for attending the program. These findings are consistent with the theory of Support Accountability [48], a theory of behavior change developed specifically to account for the complex interaction of a health professional and consumer when communicating through electronic health technology. Under the lens of this theory, a person will be highly motivated to execute a healthy behavior if they know that a health professional, who they have a positive social relationship with, is waiting for them at a specific time through a technological medium. Although the inclusion of a trainer with remotely delivered electronic health technologies will heighten the costs of this program in a real world setting, supervised teleexercise might be ideal for people who lack sufficient motivation or knowledge to independently manage their own health through participation in exercise. Future studies may benefit from including behavior change theories that promote self-management of exercise behavior [49], which was beyond the scope of this study.

Since the primary aim of this study was to determine the feasibility of employing remote monitoring technology, this study used upper body arm ergometers, an established mode of aerobic exercise. However, the physiologic demand of these devices most likely contributed to the plateau in moderate exercise performed by participants, observed at approximately the fourth week of the intervention. Compared to traditional forms of aerobic exercise that utilize the lower limbs (eg, walking, jogging, cycling), arm ergometers rely on a relatively lower muscle mass in the upper arms, making participants more prone to early-onset fatigue [50]. Thus, to enhance training progression, as well as increase the effects of teleexercise on a wider variety of health-related outcomes, there is a need to

identify exercise options that are effective in the home over a longer period of time targeting various types of activities for improving strength and cardiorespiratory fitness. Thus, future studies should pursue equipment that is cost effective and provides a variety of easily accessible and usable exercise options (eg, resistance bands, cuff weights, and adapted exercise equipment).

The demands on telecoaches were comparable to typical supervised exercise programs performed onsite, but the participants were much less burdened. The total demands on the telecoaches included virtually meeting with participants 3 days per week through the teleexercise system, two on-site visits to set up and withdraw the equipment, and the flexibility to reschedule an exercise session to a later date at the participant's request. Participants appreciated the interaction and support they received from the telecoach. However, to improve sustainability in the community, promoters of teleexercise should develop strategies that potentially reduce the cost on the participant and/or time required by the telecoach. Such strategies could include increasing the participant-to-telecoach ratio (ie, group-based exercise) or tapering the amount of time spent with a telecoach throughout the study.

Teleexercise technology may serve as an adjunct to using fitness centers for promoting exercise in persons with SCI. Our findings suggest that the barriers of transportation, time to get to and from the exercise site, and inaccessible facilities prevent persons with SCI from engaging in regular exercise at local fitness centers. Teleexercise might address these issues by allowing fitness trainers to conveniently reach a wider variety of populations that desire supervised exercise training. Given that many fitness facilities often experience low volume during work hours (9 am to noon and 2 pm to 4 pm) there is potentially a 5-hour window for fitness professionals to serve as telecoaches and provide home exercise to people with disabilities for a nominal fee or as a small addition to their annual membership fee. Specific strategies for providing this online service warrant further investigation.

Limitations

There were a few limitations in this study. First, the limited sample size prohibited statistical analysis. Second, participants might have been reluctant to express their negative opinions or criticisms of the teleexercise program to the researcher since the interviewer was a telecoach. Future studies should use independent evaluators to collect pre/post data who are not part of the telecoaching intervention. Lastly, exercise records and minutes of moderate exercise held no specific a priori criteria for feasibility.

Conclusion

Persons with SCI experience substantial barriers to participating in community-based exercise. This Web-based intervention demonstrated good feasibility for remotely monitoring a moderate intensity exercise program for persons with SCI in the comfort of their home. Participants expressed high acceptability of the program, which they attributed to its accessibility, convenience, and the interpersonal interaction with the telecoach. Health professionals should consider expanding programs to include teleexercise for community-dwelling persons with SCI, especially among those living in rural areas who have limited or no access to onsite programs. The findings from this study are encouraging and merit further investigation in larger clinical trials.

Authors' Contributions

All authors contributed to the design of this study. CSB and BL constructed the initial draft of the manuscript. All authors contributed to the review of this manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Example of the interview question guide used by the interviewer.

[PDF File (Adobe PDF File), 209KB - rehab_v3i2e8_app1.pdf]

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Abbreviations

HRR: heart rate reserve
PASIPD: Physical Activity Scale for Individuals with Physical Disabilities
QLI-SCI: Quality of Life Index—SCI Version
RPE: rating of perceived exertion
SCI: spinal cord injury
SWLS: Satisfaction with Life Scale

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