A Novel Knee Rehabilitation System for the Home
Baillie, Lynne; Ayoade, Mobolaji

Published in:

DOI:
10.1145/2556288.2557353

Publication date:
2014

Document Version
Peer reviewed version

Link to publication in Heriot-Watt University Research Portal

Citation for published version (APA):
A Novel Knee Rehabilitation System for the Home

Mobolaji Ayoade and Lynne Baillie
ITT Research Group, School of Engineering and Built Environment,
Glasgow Caledonian University, UK
{Mobolaji.ayoade, L.baillie}@gcu.ac.uk

ABSTRACT
In this paper, we describe the design and evaluation of an interactive home-based rehabilitation visualisation system used by a wide variety of ages (users in our studies were aged from 47-89) to undertake rehabilitation in the home following knee replacement surgery. We present the rehabilitation visualization system and the results of a randomized controlled study in which we investigated the usability and feasibility of the system in the home. We found that our users were able to use the system successfully for their rehabilitation with improved rehabilitation outcomes after 6 weeks when compared to the current rehabilitation care. Finally we highlight the lessons learned which will benefit prospective designers of home rehabilitation technology in ensuring successful home evaluations in clinical rehabilitation.

Author Keywords
User Design; Usability; Home Knee Rehabilitation; Inertial Sensors; Visualizations.

ACM Classification Keywords
H.5.2. Information interfaces and presentation: Miscellaneous.

INTRODUCTION
Osteoarthritis of the knee is a degenerative joint disease associated with ageing, characterised by excessive pain and disability of the knee. Knee replacement (KR) is an effective treatment for severe knee osteoarthritis where the worn knee joint is replaced with ceramic or metal implants. However to optimise functional recovery a period of physical rehabilitation is routinely prescribed [17]. Over 80,000 knee replacements are performed per year [1] in the UK and the bulk of the acute post-operative rehabilitation takes place in the patients’ homes and not in the hospital or rehabilitation centres. As life expectancy is rising across the world, the population of older adults affected by osteoarthritis and needing home rehabilitation is set to increase. After surgery the patients use exercise handbooks and/or DVDs for their home rehabilitation. Patients are also often supported during their home rehabilitation with a phone call check up in the second week of their home rehabilitation. There is growing evidence that the exercises provided in the handbook and shown in the DVD’s are less than ideal because they can be repetitive, boring [35] and lack a reasonable level of interactivity, which could lead to low adherence [23] and therefore poor rehabilitation outcomes. This is particularly problematic for KR because it can lead to: failure to recover suitable knee range of motion (ROM), lead to the inability to safely carry out activities of daily living [30]; or revision surgery and reduction in the lifespan of the new joint [21].

In order to improve the effectiveness of home rehabilitation, it has been suggested that the presence of a physiotherapist in the home or return visits to a community based rehabilitation centre could ensure the correct performance of the exercises and provide motivation to exercise [9]; however this method is less than optimal because it can be very expensive and time consuming for health professionals and patients. Thus there has been a growing interest in the development and evaluation of enabling rehabilitation technologies that could provide some form of feedback and motivation for various health conditions. These health conditions include but are not limited to stroke rehabilitation [26], falls prevention [34] and knee replacements [3, 33]. Some of these systems have been shown to motivate and promote enjoyment of rehabilitation activities but there is limited evidence supporting their clinical effectiveness [12].

Furthermore, the majority of the studies of home rehabilitation have been carried out in controlled environments, such as laboratories [8] or rehabilitation centers [24]. Only a few studies have focused on truly home-based systems [2]. In those home-based studies, health professionals have retained control over the system and supervised the exercise sessions with patients over the Internet [22]. This would result in extra workload for the therapists in countries like the UK where the patients have limited contact with therapists during the home rehabilitation period. The performance of these home-based systems in the home under the full control of patients over the full term of their rehabilitation has thus not been reported upon before. We designed a home-based system, which would be controlled by the patients themselves. We
also evaluated the system in the home, as we believe that the true potential of home rehabilitation technology cannot be verified without testing it thoroughly in the home, which is the setting for knee rehabilitation. This placed strict constraints on us as designers to create a system that was capable of being used over a 6 week time period by the intended users’ i.e. older people, with an average age of 68 years [28]. To our knowledge, this is the first reported study of the use of motion sensors, visualization and video conferencing by patients on their own in their homes to aid their rehabilitation after knee surgery. We present evidence of its effectiveness in improving rehabilitation outcomes, patient experiences, and communication with therapists. Finally we highlight the lessons learned which will benefit prospective designers of home rehabilitation technology in ensuring successful home evaluations in clinical rehabilitation.

RELATED WORK
In a survey, Zhou et al. [37] identified that seniors (> 65 years) have not adopted technology as part of their rehabilitation because most systems have complex set ups, are expensive, often have poor interactivity and may require large or fixed spaces which may not be available or wanted in people’s current homes. There have however been recent developments in commercial video game technologies, gesture and motion sensors, which are cheap, require less space and are simpler to use allowing researchers to adapt these technologies for rehabilitation purposes [12]. The use of commercial gaming in rehabilitation has been shown to have the potential of improving motivation and adherence to rehabilitation programs by facilitating the enjoyment of physical activities, but they do not necessarily promote correct performance of rehabilitation exercises as the game controllers capture users' gestures or gross movement patterns [32].

Camera based systems such as Animal Feeder [6] Silver fit [24] and the Kinect allow easy full body interaction without the need to wear markers or sensors. However a knee replacement patient must sit or lie on a bed or chair in a comfortable position while performing the exercises and the cameras may not be able to separate the patient from the furniture causing the system to incorrectly show the users movement [13]. Other popular commercial game technology involving the use of hand held controllers such as the Nintendo Wii are unsuitable because of their inability to capture fine-grained movements [7], also they were not built to be body worn sensors and wearing two on one leg could be uncomfortable for the patients who has just undergone knee surgery.

Other types of sensing systems suitable for home use include smartphones with in-built motion sensors. For instance, Doyle et al. [8] used the accelerometer in an iPhone strapped to the body to provide visual feedback on correct pace and angle of motion and found that the visual feedback encouraged the correct performance of rehabilitation exercises. However this set up is unsuitable for knee rehabilitation because multiple phones would be required and interaction would be cumbersome. Another study used a self-contained wearable knee device for visualizing knee rehabilitation exercises that indicated how straight the knee is during exercises [2]. While this setup is suitable for knee rehabilitation, the amount of feedback provided was very limited and does not cover the full range of knee rehabilitation exercises. Another study used wireless motion sensors to provide real-time visual feedback during lower limb rehabilitation in a controlled setting [36] but the usability in an uncontrolled setting is yet to be evaluated. In this paper we report on the inertial sensors that we used to overcome the limitations posed by other motion sensing technologies. These sensors were found to be easy to use as well as comfortable for the user to wear [3].

The studies discussed above had relatively short evaluation durations of two days for investigating the effectiveness of their knee rehabilitation systems. The recommended duration for knee rehabilitation after knee surgery is six weeks; therefore two days could be viewed as too short a time to test such a system fully. Our study investigated the effectiveness of the Rehabilitation Visualisation System (RVS) over the entire period (6 weeks) of acute rehabilitation following knee replacement surgery.

Other longer-term studies in rehabilitation like Russell et al.’s. [25], have delivered supervised home-based therapy sessions over video calls. Yet after the sessions patients still have to continue in unsupervised sessions before the next supervised session. To overcome this, Piqueras et al [22] used wireless motion sensors for an interactive rehabilitation system that allows the patient to be monitored by therapists’ in-between sessions. Their system was therapist centered and only limited feedback on progress was given to the user. Our system is patient centered requiring no intervention from the therapists, and we provide rich feedback on performance and progress in unsupervised exercise sessions. We integrated a video conferencing application to our system to help the patient discuss their rehabilitation progress with a therapist and get additional feedback on their performance.

Many studies on rehabilitation technology have employed user-centered approaches to the design of rehabilitation tools for seniors [11, 34]. The result has been more usable and acceptable applications, as identified by Kujala [15]. We also employed the principles of user-centered design throughout the phases of the development of the system.

The majority of the studies in rehabilitation technology have focused on usability metrics such as ease of use [10], effectiveness of visual feedback [2] and satisfaction of the target population [12]. However, it has been found that usability metrics alone will not cover the full extent of the users experience of rehabilitation over time [14]. We therefore wanted to explore some additional metrics such as
quality of life and improved knee function that are meaningful to the patients and health professionals.

The first novel part of our work is in the combination of: the sensors, video conferencing, wedge (for correct sensor-body alignment calibration) and the user designed interfaces, which incorporated designs directly from people who had undergone knee surgery). The second novel part of our work was to go beyond the normal usability evaluation and in order to do this we needed to carefully ensure that our rehabilitation visualisation system could be used by patients to undertake their 6 week rehabilitation programme in their own home unsupervised. In the next section, we will describe the design process and evaluation protocol for the rehabilitation visualisation system.

METHODS

Figure 1 shows all the steps leading up to the home study, which is reported in this paper.

![Figure 1. Research phases.](image1.png)

The study phases are established HCI practices in Participatory Design (PD). However, very few studies on rehabilitation technologies have gone further than the laboratory or controlled environments to real world contexts [4]. The home study was carried out in unsupervised settings and thus would provide valuable design insights for future rehabilitation systems.

User Requirement Gathering

The clinical pathways for knee replacement intervention in two hospitals were studied using semi-structured interviews and field observations/shadowing with 2 orthopedic surgeons and 2 physiotherapists in order to identify the requirements for effective knee rehabilitation in the home. We found that the exercises prescribed are aimed at restoring strength and range of motion of the operated leg. Most patients do these exercises on their own in their homes with the aid of a handbook. The list below summarizes initial requirements used in developing a low fidelity exploratory prototype.

- Patients require feedback on correctness of movement during exercises.
- Patients need to be motivated beyond the initial relief from excessive pain – which usually occurs almost immediately after surgery.
- Easy-to-use home technology that is suitable for frail seniors to setup and use on their own.

User Design Workshop

We undertook a design workshop that was published in [3] with eleven former knee replacement patients to explore user design requirements. The first prototype rehabilitation visualisation system was presented to them and consisted of two inertial motion sensors and a low fidelity animation on a laptop. The workshop was structured around discussions on past rehabilitation experiences, the prototype rehabilitation visualisation system and the participants design ideas for the visual elements. Figure 2 shows the user sketches for knee ROM. The participants wanted color-coded feedback on knee range of movements, a full body figure showing the appropriate posture of the exercises and a weekly progress screen.

![Figure 2. User sketches (a) knee ROM (b) height of leg.](image2.png)

Additional requirements not shown in the Figure 2 include: a repetition counter, and a timer. All of the participants felt the use of the prototype rehabilitation visualisation system was appropriate and relatively easy to use.

System Description

Rehabilitation Visualization Interface

We created the final design based on our findings from the design workshop and previous discussions with health professionals. Figure 3 shows a typical visualization for the knee replacement rehabilitation exercises. (A) is the guide mannequin that shows the user how to correctly perform the exercises at the optimum pace. This guide could be minimized at anytime. (B) is the real-time feedback on the user’s movements. The whole body was used to provide guidance on correct posture.

![Figure 3. ‘Straight leg raise’ exercise visualization.](image3.png)

(C) is the graphic (fan) with changing gradient of colors (red to green) was used to show the users range of motion in real-time during each repetition: a deep green represented the recommended range of movement; a light green represented an ‘almost there’ range; a yellow indicated a minimum range and a red indicated a poor range. (D) Is a
colored repetition counter bar that allows the user to see their performance for each repetition completed.

![Inner Range Quads Performance Summary](image)

Figure 4. Progress chart.

Figure 4 shows a typical progress chart that tracks the users’ quality and quantity of motion in the affected limb over an extended period of time. This way, the user could tell how much progress they had made with each exercise in terms of the ability to move the affected joint and the average number of repetitions completed per week. Both the target users and the health professionals suggested that progress should be shown on a weekly basis rather than a daily basis because not every exercise session will show progress.

**Hardware Description**

We built inertial motion sensors that could be easily attached to the thigh and leg with elastic Velcro straps. The sensors are charged over standard mini-USB ports. The sensors labels contain a text and an arrow showing the up direction for correct placement (Figure 5). An inertial sensor unit consists of three sensors a triple-axis gyroscope, triple-axis accelerometer, and triple-axis magnetometer.

![Wireless inertial sensors](image)

Figure 5. Wireless inertial sensors.

The user’s movement is wirelessly transmitted to a laptop running the rehabilitation software, previously described. For an inertial sensor to accurately track body movement the sensor-body offsets must be estimated and corrected using a calibration procedure [19]. We used a simple static calibration procedure that requires the user to place the knee on a wedge of a known angle (140 degrees).

Figure 6 shows a typical home setup. In a typical home set up the rehabilitation software runs automatically once the laptop is switched on and a user interacts with the rehabilitation software using either the keyboard or a remote control. To use the system, a patient sets up the laptop in any comfortable location in the house e.g. bedroom, wears the sensors and use the blue knee wedge as shown in Figure 6 while during home exercise sessions. The remote control was used because it would be difficult for knee patients to reach the laptop. Furthermore most seniors are familiar with a TV remote.

![A typical home set up](image)

Figure 6. A typical home set up.

**Pilot Usability Study**

We carried out two pilot usability studies with six former knee replacement patients after we developed a working rehabilitation visualization system. One study was carried out in the laboratory so that the system could be evaluated in a controlled environment. The other study was carried out in participants’ homes (the intended environment) [3]. We found that the rehabilitation visualization system enabled the participants to perform the exercises more correctly as they paid attention to the pace, range of movement and the number of repetitions completed. On the other hand, certain usability issues were identified with regards to the angular ranges we had adopted – the angles seemed to be too difficult for the users to achieve.

**Randomized Controlled Home Study**

The main focus of this paper is the randomized controlled home study we conducted with knee replacement patients in the acute phase of their post-operative rehabilitation for a period of six weeks. The objectives of the study were as follows:

1. To explore the user experiences of our rehabilitation visualization system following knee replacement surgery.
2. To investigate the effects of using our system compared to standard care following knee replacement surgery.
3. To explore the use of video conferencing, which is used in our system, as an alternative to the phone call checkup.

**Ethical Approval and Recruitment**

The NHS West of Scotland Research Ethics Committee 5 approved the study (Ref: 12/WS/0151). All patients scheduled to undergo their first unilateral total knee replacement at the hospital were eligible for inclusion into the study. Patients with severe visual or cognitive impairments (determined by the treating surgeon) and non-English speakers were excluded from the study. The surgeons screened the patients and provided a summary of the trial to the patients at the preoperative assessment clinic. They then signposted the patients to the researchers who answered any further questions the patient might have. The time between the preoperative assessment clinic and surgery varies between a few days to months. Informed
consent was obtained from the patients when they arrived at the hospital a day before or the day of surgery or postoperatively before discharge.

Randomization
Baseline measures were obtained by the researchers just before a patient was discharged. The patients were randomized after the baseline measures had been obtained. The randomization was stratified on age (<69 or >69 years) and sex to ensure group comparability. The participants were randomly assigned into either the control group or the rehabilitation visualization system (RVS) group using an offsite computer generated randomization system. Both groups received the standard care handbook but only the RVS group received the system.

The Home Rehabilitation
Patients received the exercise handbook and DVD provided by the hospital as part of their standard care. In addition a therapist called each patient on a one off basis in the 2nd week from discharge to check up on rehabilitation progress. For participants in the RVS group, we setup the system within 10 days of their getting home. The setup procedure consists of a brief training session on how to use the various components of the system. The participants were advised to use the rehabilitation visualization system each time they exercised. The following are the steps involved in using the rehabilitation visualization system.

- Setup: switch on laptop and sensors, put on the sensors
- Select exercise from the exercise menu
- Calibrate the sensors using the wedge
- Undertake the exercise
- Select the next exercise
- Quit when session is completed.

The participants could also view their progress at the end of every week from the exercise menu. They received a video call in week 3 from the therapist and in the sixth week they returned to the hospital for a clinical checkup.

Outcome Measures

Functional Performance Assessments
Knee range of motion is an important clinical parameter following knee replacement surgery. It is a predictor of independence and safety of the patients when carrying out activities of daily living [16]. The active knee ROM was measured using a standard goniometer. Three measurements were recorded and the average used for analysis.

Health Surveys in Orthopedics
We used the Oxford knee score (OKS) - a self-reported condition specific measure that provides a measure of knee condition before and following knee replacement surgery. It consists of 12 items with 5 possible ratings and is widely used as an outcome measure following knee replacement surgery [20]. The scoring system ranges from 0 – 48, with 48 meaning no problem with the knee. We also measured the participants’ general health using the short form health survey SF-12. It consists of 12 questions with 5 response scales. We report the mental component summary (MCS) scores in this paper.

Rehabilitation Experience
Each participant completed a background questionnaire during the baseline measurement i.e. shortly before discharge from the hospital. Participants also completed an intrinsic motivation inventory2 (IMI) at the end of the 2nd and 6th week. The Intrinsic Motivation Inventory (IMI) was used to assess participants' subjective experiences related to their home rehabilitation and was completed by all the participants. We selected interest/enjoyment, perceived competence, pressure/tension and effort subscales based on our research objectives.

Adherence to exercise program
A post study questionnaire was used to assess users’ experiences in terms of adherence and compliance levels to rehabilitation program on a scale of 0 – “I did few or none” to 3 - “I did the recommended number daily”. They were also asked to list the factors influencing their compliance to the rehabilitation program. We also captured any particular challenges the users might have faced using the system.

Usability
The System usability scale (SUS) was used as a self reported measure of perceived usability of the rehabilitation visualization system [27]. The SUS consists of 10 question and an answer rating on a 5 point Likert scale from 1- strongly disagree to 5-strongly agree.

RESULTS
The group difference was analyzed using the Mann-Whitney test for two independent samples.

Participants
Twenty-one participants started the home study. The demographic information is shown in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>RVS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median Age (Range)</td>
<td>71(47 - 85)</td>
<td>69 (50 - 78)</td>
</tr>
<tr>
<td>Female</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Male</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Novice user</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Occasional user</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Experienced user</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Excluded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dropouts</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Complications</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Net Participants</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 1. Baseline characteristics of both groups (RVS= Rehabilitation Visualization System).

2 http://www.selfdeterminationtheory.org/questionnaires/
However only data from 15 participants were included in the analysis. This was because three participants dropped out of the study while another three were excluded because they had medical complications.

**User Experience Outcomes**

**Usability**
The mean SUS score for the RVS group was 95.83 (SD = ±6.12). The 95% confidence interval is (91.13 – 100.54). However, 2 participants that dropped out of the study because of problems with the remote control as windows updates was interfering with the remote control script. Another participant had problems with the remote control but continued using the keyboard until the problem was fixed. A fourth participant encountered problems with the charging port for the sensors.

Some of the user comments on the different rehabilitation aids can be seen in Table 2.

<table>
<thead>
<tr>
<th>Handbook/DVD</th>
<th>RVS</th>
</tr>
</thead>
<tbody>
<tr>
<td>“When I’m sitting down and watching the TV, I’m reading the book. Handy”</td>
<td>“It is easier and more interesting because you can watch your progress. It will be boring otherwise”</td>
</tr>
<tr>
<td>“Book explained what you were expected to achieve”</td>
<td>“Encourages completion of 15 repetitions. It helped me to monitor my improvement”</td>
</tr>
</tbody>
</table>

**Table 2. User comments on the tools used.**

From the user comments, it is evident that the rehabilitation visualization system made the home rehabilitation more engaging – actively encouraging better performance.

**Motivation**
The results of the average rating (maximum rating of 7) for the four subscales of intrinsic motivation inventory are shown in the Table 3. The values displayed are mean and standard deviation. On the interest/enjoyment subscale both groups had above average intrinsic motivation, but the control group had lower levels than the RVS group in week 2. In week 6, the trend was reversed with the control group having higher levels of intrinsic motivation. On the perceived competence subscale, the RVS group felt more competent than the control group in week 2. However by week 6, the control group felt a lot more competent while on the effort/importance subscale, both groups placed almost an equal amount of importance on the rehabilitation exercises in week 2. It is only the control group that reported increase in the effort/importance; the RVS group remained the same.

<table>
<thead>
<tr>
<th>Wk. 2</th>
<th>Control</th>
<th>RVS</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Competence</td>
<td>5.8 ±1.1</td>
<td>6.1 ±1.2</td>
<td>0.371</td>
</tr>
<tr>
<td>Effort</td>
<td>6.5 ±0.8</td>
<td>7.0 ±0.8</td>
<td>0.492</td>
</tr>
<tr>
<td>Interest</td>
<td>5.9 ±1.1</td>
<td>6.5 ±1.5</td>
<td>0.232</td>
</tr>
<tr>
<td>Pressure</td>
<td>2.8 ±1.5</td>
<td>2.5 ±1.5</td>
<td>0.435</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wk. 6</th>
<th>Control</th>
<th>RVS</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Competence</td>
<td>7.0 ±0.8</td>
<td>7.0 ±0.7</td>
<td>0.505</td>
</tr>
<tr>
<td>Effort</td>
<td>7.0 ±0.6</td>
<td>7.0 ±0.8</td>
<td>0.352</td>
</tr>
<tr>
<td>Interest</td>
<td>7.0 ±1.1</td>
<td>6.3 ±1.1</td>
<td>0.234</td>
</tr>
<tr>
<td>Pressure</td>
<td>1.0 ±1.4</td>
<td>1.0 ±1.0</td>
<td>0.469</td>
</tr>
</tbody>
</table>

**Table 3. Intrinsic motivation subscales.**

The pressure subscale shows that both groups had similar levels of pressure, which reduced by the 6th week.

**Adherence to Rehabilitation Program**
The participants were asked to describe their average compliance to the recommendations of the health professionals – 4 times daily. Table 4 shows there were similarities in the compliance profile between the two groups.

<table>
<thead>
<tr>
<th>Adherence Level</th>
<th>Control</th>
<th>RVS</th>
</tr>
</thead>
<tbody>
<tr>
<td>I missed many days (&lt; 60 %)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>I missed a few days (60 - 80 %)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>I did &lt;4 times daily (80 – 90 %)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>I did 4 times everyday (&gt; 90 %)</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

**Table 4. Adherence profile across both groups.**

It seems the control group reported higher adherence to the exercises but not significantly different (p = 0.379). However, when we probed further by asking them to list the top 3 factors that influenced their adherence level, the following themes emerged:

- Exercise burden: 5 of the RVS group reported that 4 times a day was too much given the average exercise session of 40 minutes. Three of the control group expressed similar sentiments. A typical comment made by the participants was that “... not enough time and you get exhausted”.
- Family support: 3 of the participants felt they were able to undertake the exercises because of the family support they received as evidenced by this comment: “My husband and son motivated me to go on”.
- Health: 4 of the participants that missed a few days cited poor health or pain as the reason for non-compliance while a participant attributed her good health as one of her factors for full compliance.
• Fitness: 4 of the participants wanted to get back to full fitness quickly so that they could either go back to work or independence. A typical comment “the desire to get back to full fitness motivated me.”

• Commitments to: family such as holidays and funerals (n=1), the research (n=3) and the hospital staff (n=2) were also cited as motivators for various levels of compliance.

Communicating Progress
The therapist during the video call check up could observe the progress charts of the patients and see and talk to the patients. Most of patients reported that they felt more confident discussing their performance with the therapist because they could point out when they had achieved a green (good) performance. A typical conversation between the patient and therapist is shown in Figure 7.

The use of the video call and rehabilitation visualization system (RVS) during check up opened up new possibilities for effective check up as evidenced in the therapist’s comments “I could identify which exercises require more effort” and “previously patients had difficulty visualizing what constitutes 90 degrees of knee flexion”.

Health Outcomes
Improvements in knee function and general health
For the SF12 the mental component of health (MCS), RVS group had a percentage improvement of 9.8% compared to -1.4% for the control group. The absolute change and improvement from week 1 indicates that the RVS group had slightly better recovery in terms of their mental health (median change: Control = -2.8, SD = 10.2; RVS = 3.1, SD = 11.5; p = 0.140). The negative improvement for the control group implies that some participants recorded a decrease in the SF12 score after 6 weeks.

For the subjective knee function (measured by the Oxford Knee Score), both groups reported improvement in the knee score. The absolute change from week 1 by week 6 tended towards statistical significance (median: Control = 17, SD = 7.8; RVS = 23, SD = 8.7; p = 0.109).

For the knee flexion, the RVS group were significantly worse than the control group in Week 1 (median: Control = 81 degrees, SD = 11.9; RVS = 69 degrees, SD = 9.7; p = 0.047). However by week 6, both groups had comparable knee flexion (median: Control = 105 degrees, SD = 14.0; RVS = 96 degrees, SD = 8.9; p = 0.478). The RVS group had greater improvement compared to the control group as shown in Figure 8. This improvement suggests a trend toward significant improvement with a p-value of 0.06.

Figure 8. Boxplot of improvement in knee flexion.

It can also be seen that some of the control group had worse knee flexion than at the start (negative change) while none of the RVS group had worse knee flexion.

Similarly, for the knee extension assessments, it appeared the RVS group was worse off than the control group (P = 0.064) at the start in week 1. However at the end of the rehabilitation period, the RVS group had significantly
greater improvement than the control group (p = 0.002) as shown in Figure 9. In addition, the negative improvement observed in Figure 9 in the control group indicates that most participants in the control group got worse (four out of seven). On the other hand, most of the participants in the experimental group improved (seven out of eight).

**DISCUSSION**

**Challenges in designing rehabilitation technology**
Our experiences show the complexity of designing rehabilitation systems that fits with both patients and therapists goals. We had engaged representative users in the design of the rehabilitation visualization system and most of the design decisions were made from their point of view. The following themes emerged from our work.

*Safely encourage correct performance*
The health professionals were concerned about the safety of using the rehabilitation visualization system for unsupervised home exercise sessions. Their desires were expressed through the emphasis placed on correct performance. We have demonstrated that seniors can safely use a rehabilitation visualization system designed to safely encourage correct performance by adopting relaxed angular targets suggested by the physiotherapists. No adverse effect was experienced by the users as a result of using the technology for their rehabilitation but seniors could be frustrated when things did not work as expected.

*Motivation*
Our findings show that the motivation to exercise following total knee replacement surgery could be higher than previously thought [38]. It could be concluded that for certain rehabilitation scenarios such as after surgery, patients could be more motivated than other non surgical settings like stroke rehabilitation [4]. The main requirements identified for post surgical rehabilitation was correct performance. However it was observed that motivation was improved with the use of the rehabilitation visualization system during the early stages. The motivation however decreased as recovery progressed but did not affect adherence. The reduction in motivation levels observed in the rehabilitation visualization system group might be connected to the safe targets adopted. Comments were made about the system becoming a bit easy for them as their recovery progressed. A possible solution would be to increase the difficulty of the targets as recovery progresses.

*Usability*
The high system usability scores demonstrate that the system and setup was generally acceptable to the seniors. Seniors successfully managed two inertial sensors and a laptop on their own i.e. charging, wearing and switching on/off. The calibration was considered simple and relatively accurate using the knee wedge. We found the therapist-measured knee ROM at the end of the rehabilitation period corresponds to the progress charts. Designers could improve the chances of adoption of technology by seniors, especially those without prior computer experience, if they include simple and robust interaction techniques such as a remote control – a familiar interface for seniors.

**Role of rehabilitation technology**
All the participants agreed that the visualization of home physiotherapy exercises helped ensure correct performance of the exercises.

*Improve recovery*
The rehabilitation visualization system group showed significant improvement in knee ROM when compared to the control group. This implies that home rehabilitation technology could improve rehabilitation outcomes. In all the other measures the rehabilitation visualization system group outperformed the control group. A minimally clinical significant difference of greater than 3 points [20] was observed in the OKS. Although not significantly (p > 0.05), these findings suggest that without the rehabilitation visualization system some patients got worse. Our findings provide evidence that patients benefit more from having an interactive rehabilitation visualization system at home as a result of the improved exercise quality [22].

*Adherence to exercise program*
The rehabilitation visualization system seemed to not have made seniors do more exercises. This is contrary to the findings of Yeh et al. [36] that such systems could increase the quality and quantity of exercises done after knee replacement. A possible explanation is that their study was done for a short time (2 days) and users behavior could change over a longer study duration. Another factor is the time it takes to complete an exercise session. It takes about 40 minutes to complete all the exercises using the rehabilitation visualization system as it enforces the correct performance and hold times, something not enforced by the booklet. This is an interesting point to note as we did find a significant difference with one of the outcome measures despite the control group reporting higher quantity of exercises. Hence designers should consider emphasizing and promoting in their design not just the quantity of rehabilitation exercises but also the quality.

*Improve general health*
An interesting result was found in the mental component of health SF12 MCS. The entire rehabilitation visualization system group had positive improvement whereas some of the control group declined. The visualization of rehabilitation exercises could possibly improve other areas of health in addition to the physical component related to exercise performance. Plausible reasons might include the mental gratification felt when targets were achieved and for some participants the learning of a new skill could have had a positive impact on their mental health.

*Improve patient-therapist communication*
The rehabilitation system and the video call check up proved to be quite useful to both patients and physiotherapists. The participants reported increased
confidence when discussing their rehabilitation progress with physiotherapists. Being able to see their feedback during and after rehabilitation sessions provided reassurance, improved feelings of competence and reduced anxiety.

**Design recommendations**

The following design recommendations emerged from our study. First, design to promote correct performance e.g. a simple traffic light type real-time color-coded feedback with 3 - 4 levels on performance motivates users to want to achieve a better score. The appropriate levels should be defined by the rehabilitation goal and the measures of improvement expected over time. Secondly, the presence of a repetition counter that shows the target number of repetitions facilitated the completion of recommended repetitions for each exercise. Thirdly, always provide progress history. While caution must be taken in the frequency of and the period to show progress, we found that a weekly period worked very well for our participants. Fourthly, display the essential movement parameters at the right level of abstraction – colored fan and bars rather than numbers. Fifth, show ideal movement side by side with user’s movement by inserting the ideal movement in a small portion of the screen compared to the users movement. This will ensure the patients are not forced to match the ideal pace and range of movement when they are still trying to recover their optimum movement in the early rehabilitation stages.

**Lessons learned**

Our strategy to obtain informed consent before surgery did not always work and we later changed the approach to anytime after surgery but before the patient was discharged. Most patients without previous experience with computing technology would decline to take part in the rehabilitation technology studies. It was also found that two participants would have benefited from multiple training sessions. Another reason for the low recruitment rate was that we had very strict inclusion and exclusion criteria. The use of stratified randomization helped promote baseline comparability between the two groups on age and sex distribution. Designing and evaluating rehabilitation systems are complex and multiple instruments should be used to capture the different facets of usability and health outcomes during long-term studies in uncontrolled settings.

**CONCLUSION**

This is the first time that we know of that a wireless motion capture based home rehabilitation visualization system has been used by users, unsupervised for their rehabilitation after surgery. By paying attention to the requirements for older adults with limited computer experience through our design workshops, pilot usability study and iterative design process, we have developed a rehabilitation visualization system that is (a) easy to use by seniors unsupervised (b) effective in ensuring correct performance of home knee exercises (c) motivates patients at the early rehabilitation phase (d) facilitates communication of rehabilitation progress with therapists (e) improve knee range of motion and accelerates functional recovery, and (f) improves the mental health of patients. Our results are limited by the small sample size so should be viewed as suggestive rather than conclusive.

**ACKNOWLEDGMENTS**

Funding for this study comes from the Medical research Council, UK, LLHW (Phase 2), Grant ID: 91021.

**REFERENCES**


