Exploring the Impact and Acceptance of Wearable Sensor Technology for Pre- and Postoperative Rehabilitation in Knee Replacement Patients

A U.K.-Based Pilot Study

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Background: Knee replacement operations are common, highly successful procedures that are increasing in frequency. The COVID-19 pandemic has emphasized the need for innovative care pathways that reduce face-to-face appointments. We report on the impact of introducing a wearable sensor for pre- and postoperative rehabilitation of 21 knee replacement patients at 2 hospitals in the U.K.

Methods: The sensor (BPMpathway; 270 Vision) was provided during joint school prior to knee replacement and stayed with the patient until a maximum of 9 weeks post-surgery. Participant progress and exercise were monitored remotely, with exercise regimens altered as required. Participants and clinicians could communicate remotely via the device.

Results: The median range of motion during the first week post-surgery was 63° (interquartile range [IQR] = 21°) and increased to 136° (IQR = 16°) by week 7. The rate of participant compliance with exercises using the device was 32.3% for thrice-daily compliance and 52.4% for once-daily compliance. The 2-way communication channel was well utilized by both participants and clinicians. We report a 35.7% reduction in face-to-face physiotherapy appointments compared with standard practice. Finally, >80% of users who completed the feedback questionnaire reported a positive experience using the device, finding it easy to understand and reporting that it motivated them to perform their exercises.

Conclusions: The use of BPMpathway was well received, effective, and reduced face-to-face physiotherapy appointments.

Clinical Relevance: Remote monitoring can reduce the burden to the outpatient physiotherapy service by supporting the post-COVID-19 surgical service recovery plans of the National Health Service and allowing patients to recuperate at home.

Knee replacements are routine procedures for managing pain, with >90,000 procedures having taken place across the National Health Service (NHS) in England between 2018 and 2019[1]. Research indicates that physical rehabilitation improves short-term outcomes following knee surgery[2]. However, with no universally accepted guidelines, post-surgical rehabilitation can vary[3]. The absence of universal guidelines may, in part, be the result of a lack of research: a 2003 U.S. National Institutes of Health consensus statement concluded that rehabilitation services are one of the most understudied aspects of the perioperative management of knee replacement patients[4]. Currently, the progress—or regression—of a patient is assessed by clinicians using a standard handheld goniometer at varying time intervals that depend on the processes within the individual hospital. Many of these standard visits have been dis-rupted by the COVID-19 pandemic, resulting in infrequent face-to-face visits and measurement of progress. The resulting fallout from the pandemic has led to a "new normal" state of health care, and with it, an increase in the demand for products and services that reduce the number of points of contact with patients along a care pathway. Furthermore, the COVID-19 pandemic has placed unprecedented strain on the NHS, deferring surgeries and creating a waiting list of up to 1.4 million patients[5]. This waiting list is expected to take between 20 and 48 months to return to pre-COVID-19 levels, at a cost to the health-care sector of approximately £2 billion[5].

Digitization is the centerpiece of the NHS's long-term plans, which include reducing outpatient visits by 33%[6]. Advances in technology, coupled with the wide-scale adoption of smartphones, have made it possible to digitize aspects of the

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joint-replacement care pathway. The use of wearable sensors by patients who are undergoing joint replacement enables at-home rehabilitation by facilitating both the tracking of patient progress and 2-way communication between patients and their health-care teams. Importantly, studies report little to no clinical cost for adopting this approach[2,7,8], which can reduce the need for face-to-face visits and identify opportunities for early intervention when a patient is not on track to recovery[9]. In contrast, conventional home-based physiotherapy can be ineffective when patients do not remember how to perform certain exercises and/or when they do not receive enough feedback regarding their progress and the role of exercise programs in their recovery[10-12]. These concerns can be addressed with wearable technology. BPMpathway (270 Vision) is a digital technology that fits within the joint-replacement care pathway. It comprises a "smart" wearable sensor and an accompanying smartphone application (patient use) or computer-based dashboard (clinician use) that is designed to support pre- and postoperative rehabilitation.

As surgeries resume for patients who were placed on the waiting list, the pressures on postoperative physiotherapy services are likely to increase dramatically. Ultimately, any technology that can streamline patient contact before and after joint replacement serves the purpose of not only decreasing infection risks but also increasing local efficiencies and aligning with the long-term plans of the NHS. The aim of this U.K.-based pilot study was to explore the feasibility of providing a customized physiotherapy service following knee arthroplasty that is based on the needs of the patient, as monitored through a remote sensor and messaging system. In order to understand if the use of a digital system could improve both the patient experience and the efficiency of the postoperative physiotherapy care provided, we sought (1) to explore if a wearable sensor would reduce the number of face-to-face physiotherapy visits and (2) to measure how well received and well utilized the messaging system was by patients and clinicians.

Materials and Methods

This prospective, observational, single-arm feasibility study investigated the use of remote monitoring for pre- and postoperative physiotherapy for knee arthroplasties. Participants undergoing total knee arthroplasty (TKA) and unicondylar knee arthroplasty (UKA) were recruited from 2 sites within the Calderdale and Huddersfield NHS Foundation Trust in the U.K. Permission to conduct the pilot was obtained via the Research and Development Department of the Trust. Written consent was obtained from all recruited participants. Participants were included in the study if they had an American Society of Anesthesiologists grade of 1, 2, or 3, and had no other factors that would make them unsuitable for discharge within 24 hours. In particular, a participant was excluded if they met any of the following criteria: living alone, a history of falls, a preoperative hemoglobin level of <10 g/dL, cardiac disease, sleep apnea, chronic obstructive pulmonary disease, chronic kidney disease, previous pulmonary embolism, a history of

heavy smoking or alcoholism, epilepsy, diabetes, or clotting disorders. Any participant undergoing other procedures at the time of the study was also excluded.

The remote monitoring device explored in this pilot study consisted of a single wearable sensor device (BPMpathway; certified CE [Conformité Européene] class 1) and an accompanying smartphone application and dashboard software (for participant and clinician use, respectively). The BPMpathway sensor is worn on the lower leg to monitor the patient's range of motion. Data are uploaded to the patient's application and the clinician's dashboard for immediate review. The application prompts patients to report pain using the Wong-Baker FACES Pain Rating Scale via the app.

Recruited participants were provided with the sensor, application, and training during preoperative joint school, at which time they were also assigned preoperative exercises. Participants conducted preoperative rehabilitation during the interval between joint school and their operation. After their operation, participants performed postoperative rehabilitation exercises until they were fully discharged from physiotherapy.

Clinicians monitored patient data, altering exercise plans accordingly and arranging phone calls or face-to-face appointments as required. Patients were advised to utilize the 2-way messaging system via the app to contact their physiotherapy team with any questions or comments. Physiotherapists monitored and responded to messages via the clinician dashboard. Data on pain, range of motion, exercise frequency, and communication were recorded and collected from the outputs of the BPMpathway sensor. User experiences were reported via a questionnaire completed by participants at the end of the study period.

At joint school, preoperative range of motion was recorded using BPMpathway. On the day of surgery (day 0), participant range of motion was measured pre- and postoperatively and participants were provided with discharge exercises. Participants were advised to exercise for at least 6 weeks postoperatively and were followed for a maximum of 9 weeks. Compliance, range of motion, self-reported pain, and communication with clinicians were recorded. The frequency of home and outpatient visits was recorded and was based on participant needs.

All recruited participants were analyzed. Any recorded range-of-motion measurements of ≥150° (beyond physiological knee range of motion and indicative of a hand test) were excluded from analysis. Linear relationships between either range of motion or flexion and time, compliance, frequency of exercise, and pain were explored using a Pearson correlation analysis. Qualitative data analysis was performed on the messages sent between participants and clinicians. Messages were read independently by 2 reviewers to generate a thematic code book. Each message was coded by 1 reviewer and separately confirmed by a second reviewer, and any disagreements were resolved by discussion. Discussion points were grouped into 7 categories: (1) practicality of rehabilitation and exercises, (2) pain/swelling, (3) progress, (4) technical queries about the device, (5) nudges from the physiotherapist to encourage

TABLE I Patient Demographics	
Participants	21
Study site 1 *(no. [%])*	8 (38%)
Study site 2 *(no. [%])*	13 (62%)
Sex	
Male *(no. [%])*	12 (57%)
Age* *(yr)*	55.08 ± 7.7
Female *(no. [%])*	9 (43%)
Age* *(yr)*	61.33 ± 9.5
Overall age* *(yr)*	57.76 ± 8.9
Height* *(cm)*	171.26 ± 10.9
Body weight* *(kg)*	91.1 ± 16.4

*The values are given as the mean and standard deviation.

exercise, (6) appointment planning, and (7) miscellaneous. At the end of rehabilitation, participants completed a feedback questionnaire using a 5-point scale for responses and were given the opportunity to provide free-text feedback. All statistical analysis was performed using SPSS version 26 (IBM). All variations were expressed as the standard deviation (SD), range, or width of the interquartile range (IQR), depending on normality.

Results

A total of 21 adult participants (16 TKA and 5 UKA) were included in the study. There were 9 female and 12 male patients with an overall mean age of 57.76 ± 8.9 years. Table I presents the demographics of the recruited participants.

In total, 1,163 days of BPMpathway use were included in the data collection and comprised 426 days of preoperative exercises (mean, 20.29 ± 19.7 days) and 737 days of postoperative rehabilitation (mean, 35.10 ± 11.2 days). Three participants did not receive the device prior to surgery; only postoperative data are available for those participants. One participant struggled with the technology and another had issues with their Wi-Fi signal, limiting data collection from them.

Across all participants, range-of-motion exercises were performed a total of 1,179 times over the 1,163 days of the study. A total of 1,135 (96.27%) of the measurements of range of motion were <150° and thus included for analysis. Participant compliance with the prescribed exercise regimen was assessed as (1) whether or not exercise was conducted 3 times
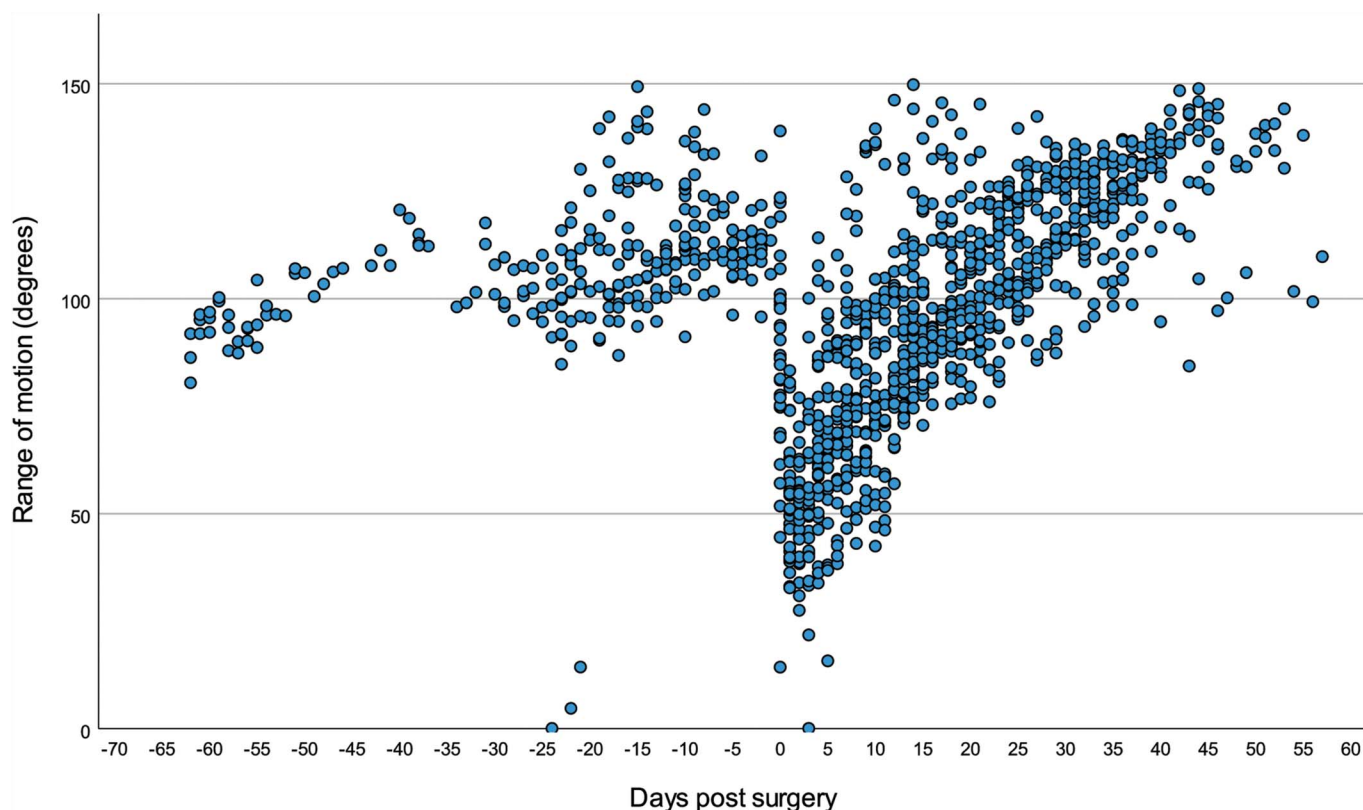

Fig. 1
Range of motion over time in both pre- and postoperative phases. Day 0 represents the day of surgery.
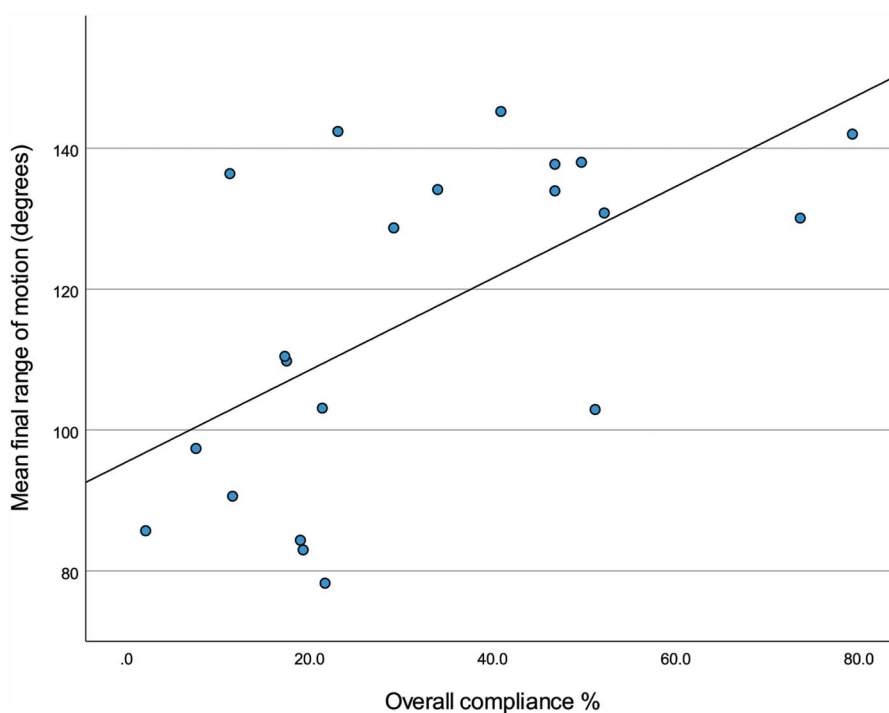
Fig. 2

Relationship between participant range of motion, as measured on the participant's final day of rehabilitation, and overall compliance with the prescribed exercise regimen (p ≤ 0.01; $R^2 = 0.373$).

daily and (2) whether it was conducted at least 1 time daily. The rate of participant compliance with exercises using the device was 32.34% for thrice-daily compliance and 52.4% for once-daily compliance. Compliance (3 times per day and 1 time per day, respectively) was higher during the postoperative phase (41% and 62.1%) than during the preoperative phase (19.6% and 34.4%). Large variation in daily compliance was observed between participants, ranging from 0% to 100% preoperatively and 11% to 100% postoperatively. Only 1 participant performed exercises to full daily compliance during the preoperative phase. In the postoperative phase, the number of participants who fully complied with their exercise regimen increased to 4.

Participants' pre- and postoperative range of motion is shown in Figure 1. Improved range of motion, and a positive correlation of range of motion with time, was observed during both the preoperative (p = 0.01; $R^2 = 0.215$) and postoperative (p ≤ 0.01; $R^2 = 0.592$) phases. The median range of motion was 63° (IQR = 21°) in the first week post-surgery and increased to 109° (IQR = 21°) in week 4 and further increased to 136° (IQR = 16°) by week 7. Although not all participants continued rehabilitation for the full 6 weeks, with exercises continuing for a mean of 32 ± 13.1 days, the median final range-of-motion measurement when exercise ceased was 129° (IQR = 43°). In both pre- and postoperative phases, thrice-daily and once-daily compliance were positively associated with a higher final-day range of motion (Fig. 2). A negative relationship between range of motion and self-reported pain score (p ≤ 0.01; $R^2 = 0.397$)

was observed, with the greatest range of motion corresponding with the lowest grade of pain.

Flexion followed a pattern similar to that of range of motion, increasing over time during preoperative rehabilitation (p = 0.01; $R^2 = 0.369$) and postoperative rehabilitation (p = 0.01; $R^2 = 0.502$). A positive correlation was observed between final-day postoperative flexion and frequency of performing exercises (p = 0.01; $R^2 = 0.282$).

Prior to the use of BPMpathway, the standard practice at these participating sites was for each patient to receive 6 at-home physiotherapy visits, which would have equated to a total of 126 face-to-face home physiotherapy visits for the 21 patients included in the current study. We report a 35.7% reduction in face-to-face visits by assigning visits according to patient requirements using BPMpathway. In our study, only 81 visits (11 outpatient appointments and 70 at-home physiotherapy visits) were required, reducing the median number of visits per participant from 6 to 4.

BPMpathway allows 2-way communication between patient and clinician. A total of 212 messages were sent during the pilot study; 35 (16.5%) were sent preoperatively, and 177 (83.5%) were sent postoperatively. The majority of participants (76.2%; 16 of 21) utilized the communication feature to contact clinicians, accounting for 47.2% (100) of the 212 messages. Multiple discussion points were covered per message (see Table II for details). Postoperatively, participants most frequently sent messages regarding progress (50% of the messages sent), technical questions (35.2%), and pain/swelling (30.7%). Clinicians primarily sent postoperative messages in response to participants on the topics of pain/swelling (21.3%), progress

TABLE II Number of Messages (Total and by Topic) Sent by Participants and Physiotherapists*

	Total No. of Messages Sent	Message Topic (no. [%])							Total No. of Discussion Points
		Practical	Pain/Swelling	Progress	Technical	Nudge	Miscellaneous	Appointment	
Participants									
Overall	100	13 (13.0%)	29 (29.0%)	48 (48.0%)	37 (37.0%)	NA	10 (10.0%)	4 (4.0%)	141
Preoperative	12	0 (0.0%)	2 (16.7%)	4 (33.3%)	6 (50.0%)	NA	3 (25.0%)	0 (0.0%)	15
Postoperative	88	13 (14.8%)	27 (30.7%)	44 (50.0%)	31 (35.2%)	NA	7 (8.0%)	4 (4.5%)	126
Physiotherapists									
Overall	112	4 (3.6%)	21 (18.8%)	40 (35.7%)	27 (24.1%)	20 (17.9%)	13 (11.6%)	13 (11.6%)	138
Preoperative	23	0 (0.0%)	2 (8.7%)	5 (21.7%)	4 (17.4%)	3 (13.0%)	9 (39.1%)	1 (4.3%)	24
Postoperative	89	4 (4.5%)	19 (21.3%)	35 (39.3%)	23 (25.8%)	17 (19.1%)	4 (4.5%)	12 (13.5%)	114

*Some messages covered multiple topics. Percentages are of the total number of messages sent in the indicated study phase. NA = not applicable.

(39.3%), and technical questions (25.8%). The next most common reason that clinicians sent messages was to "nudge" participants to perform their exercises (19.1% of the clinicians' postoperative messages).

Overall, 17 (81%) of the 21 participants completed the questionnaire. For 2 statements, "I liked using the range-of-motion sensor" and "Downloading the app was easy," 1 participant did not provide feedback. Table III reports the full results. Respondents provided favorable feedback, with the majority replying that they "agree or strongly agree" with the statements: "I liked using the range-of-motion sensor" (81.25%), "Downloading the app was easy" (93.75%), "I understood how to do my rehabilitation using the range-of-motion sensor and app" (82.35%), "The range-of-motion sensor motivated me to do my rehabilitation" (88.24%), "I felt secure with the remote monitoring as the physiotherapist could see my progress" (64.71%), "I felt secure contacting the rehabilitation team via the app" (64.71%), and "I was able to use the range-of-motion sensor by myself" (88.24%).

Discussion

Patient compliance is an important factor that influences the outcome of treatments[13]. Here we report a positive correlation between patient compliance and the degree of improvement in patient range of motion. Because of the single-arm nature of this study, it is difficult to directly compare the compliance rate of BPMpathway to standard care. Data on real-world compliance with physiotherapy after knee arthroplasty are lacking, and evidence from controlled trials is also scarce, of poor quality, and of questionable accuracy when using patient diaries[14]. What we do know is that clinical recommendations regarding changes to lifestyle, including the requirement to exercise frequently, can lead to poor adherence rates[15]. One study reported an exercise adherence rate as low as 19% in patients with chronic conditions[16]. In instances such as these, the BPMpathway sensor offers potential solutions to overcome low compliance rates, such as by (1) facilitating communication between the patient and clinician, thus creating opportunities for the patient to receive positive feedback, and (2) enabling the

TABLE III Participant Feedback from the Post-Trial Questionnaire

Feedback Question	Agree or Strongly Agree	Neutral	Disagree
I liked using the range-of-motion sensor*	13/16 (81.25%)	2/16 (12.50%)	1/16 (6.25%)
Downloading the app was easy to do*	15/16 (93.75%)	1/16 (6.25%)	0/16 (0.00%)
I understood how to do my rehabilitation using the range-of-motion sensor and app	14/17 (82.35%)	1/17 (5.88%)	2/17 (11.76%)
The range-of-motion sensor motivated me to do my rehabilitation	15/17 (88.24%)	1/17 (5.88%)	1/17 (5.88%)
I felt secure with the remote monitoring as the physiotherapist could see my progress	11/17 (64.71%)	4/17 (23.53%)	2/17 (11.76%)
I felt secure contacting the rehabilitation team via the app	11/17 (64.71%)	5/17 (29.41%)	1/17 (5.88%)
I was able to use the range-of-motion sensor by myself	15/17 (88.24%)	1/17 (5.88%)	1/17 (5.88%)

*Of the 17 questionnaire respondents, 1 respondent did not answer 2 questions.

clinician to regularly monitor patient progress. Both of these solutions have been shown to improve adherence rates[10]. For example, 18% of all clinician messages to study participants included a reminder or "nudge" for patients to perform their exercises. The frequency of clinician reminders to patients in our study highlights the potential of such a device as, without this ability to "nudge," some participants may have become nonadherent with their at-home exercises, which would have potentially led to poorer outcomes.

Communication, particularly positive feedback, between a clinician and a patient has been found to be important to ensure good levels of compliance and positive outcomes during the rehabilitation process[10,17]. Our study found that the majority of patients sent and received messages and that participants were well connected with their clinicians despite receiving treatment remotely. The progress of the patient was the most common topic of discussion, especially during rehabilitation. This finding supports the findings of other studies that have identified conversations surrounding patient progress as an important factor to consider when exploring patient compliance[10]. Interestingly, only 13% of all messages from participants and 3.6% of all messages from clinicians covered the practicalities of the exercises, suggesting that the BPMpathway sensor was intuitive to use in the majority of cases.

Studies have reported that normal daily activities require a minimum range of motion of 105° to 110°[18]. We report that this minimum range of motion was achieved in the majority of participants between weeks 4 and 5 of rehabilitation, indicating their ability to return to normal activity.

One of the aims of the NHS over the coming years is to digitize the health-care system and to reduce the overall number of patients who attend appointments in person. As such, we sought to explore how the introduction of BPMpathway affected the number of in-person visits. Our study revealed that, in comparison to standard practice, the number of face-to-face physiotherapy visits fell by 36% as a direct result of BPMpathway. This decrease in face-to-face appointments is primarily a result of the interactive nature of BPMpathway, which allowed clinicians to check up on patient progress, to provide feedback and instruction, and to remind noncompliant individuals of their exercise regimens, all of which were done remotely.

Patient feedback on using BPMpathway was very good, with >80% of all questionnaire respondents stating that they liked using the device. The feedback of participants in this study ultimately supports the notion that virtual rehabilitation can be a positive experience since it allows patients to be in control of their own progress. In addition, >80% of all respondents stated that they understood how to do their exercises, that they were able to use the device independently, and that the range-of-

motion data motivated them to do conduct their rehabilitation. The latter result is of particular importance since perceived barriers to exercise have been shown to be particularly pertinent when explaining noncompliance[10]. Thus, any device that can motivate a patient to perform their exercises may increase compliance rates in the long term. Furthermore, >90% of respondents stated that downloading the application was easy. Ease of use is particularly important because the majority of knee replacement procedures are performed in elderly patients, and it is essential that the smartphone application within BPMpathway is accessible to them.

Because of the pilot nature of this study, it was not designed to address any specific clinical questions. In addition, no control group was incorporated into the experimental design, limiting the interpretation of this work. Future adequately powered, 2-arm studies that incorporate BPMpathway into the intervention arm are needed to assess the impact that BPMpathway may have on clinical and patient-reported outcomes.

Conclusions

In this study, we found that BPMpathway was able to track patient range of motion across all weeks of the study. Its communication features were well utilized by both participants and clinicians to engage in discussions regarding rehabilitation. As a result of the BPMpathway sensor, face-to-face visits were reduced by 36%—an important result when bearing in mind the ramifications of COVID-19 on health care. The vast majority of participants who completed the questionnaire stated that they enjoyed using the device, were able to use it independently, and were motivated to continue with their rehabilitation. Future work is now required to fully understand the clinical and economic improvements that large-scale BPMpathway adoption could generate. ∎

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