Supporting patients to prepare for total knee replacement: evidence-, theory- and person-based development of a 'Virtual Knee School' digital intervention

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Running title

Development of a Virtual Knee School

Data availability statement

The data that supports the findings of this study are available in the supplementary material of this article where appropriate. Additional data supporting the findings of this study are available on request from the corresponding author but are not publicly available due to privacy or ethical restrictions.

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Conflict of interest disclosure

The authors declare that they have no competing interests.

Ethics approval statement

Ethical approval for Phase 1b and Phases 2–4 was gained from the London - Riverside Research Ethics Committee (REC) (19/LO/0813) and Yorkshire and The Humber - Bradford Leeds REC (20/YH/0095) respectively. Phase 1a was a rapid review so did not require ethical approval. All participants provided electronic informed consent prior to participating. The project was performed in accordance with all relevant guidelines and regulations, including the Declaration of Helsinki.

Patient consent statement

N/A

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Registration

ISRCTN registration of the overall project was obtained on 24th April 2020 (ISRCTN11759773).

Authors' contributions

AMA led the study conception, study design, data acquisition, data analysis, data interpretation, drafting the manuscript, and revising the manuscript. GAM, CC, and ACR contributed to the study conception, study design, data interpretation, and revising the manuscript. JJ, TOS, and LY contributed to the study design, data interpretation, and revising the manuscript. All authors read and approved the final manuscript.

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Abstract

Introduction

Digital delivery of pre-operative total knee replacement (TKR) education and prehabilitation could improve patient outcomes pre- and post-operatively. Rigorously developing digital interventions is vital to help ensure they achieve their intended outcomes whilst mitigating their potential drawbacks.

Objective

To develop a pre-operative TKR education and prehabilitation digital intervention, the *'Virtual Knee School'* (VKS).

Methods

The VKS was developed using an evidence-, theory- and person-based approach. This involved a mixed methods design with four phases. The first three focused on planning the VKS. The final phase involved creating a VKS prototype and iteratively refining it through concurrent think-aloud interviews with nine patients who were awaiting/had undergone TKR. Meta-inferences were generated by integrating findings from all the phases.

Results

Most participants found the VKS prototype acceptable overall and considered it a valuable resource. Conversely, a minority of participants felt the prototype's digital format or content did not meet their individual needs. Participants' feedback was used to refine the prototype's information architecture, design, and content. Two meta-inferences were generated and recommend:

1. Comprehensive pre-operative TKR education and prehabilitation support should be rapidly accessible in digital and non-digital formats.

2. Pre-operative TKR digital interventions should employ computer- and self-tailoring to account for patients' individual needs and preferences.

Conclusions

Integrating evidence, theory, and stakeholders' perspectives enabled the development of a promising VKS digital intervention for patients awaiting TKR. The findings suggest future research evaluating the VKS is warranted and provide recommendations for optimising pre-operative TKR care.

Patient or Public contribution

Patient and Public Involvement (PPI) was central throughout the project. For example, PPI representatives contributed to the project planning, were valued members of the Project Advisory Group, had key roles in developing the VKS prototype, and helped disseminate the project findings.

Keywords

Total knee replacement; digital intervention; pre-operative education; prehabilitation; intervention development; mixed methods

Introduction

Total knee replacement (TKR) is a transformative operation for many patients with end-stage knee osteoarthritis (1). Correspondingly, the worldwide demand for TKR is high and growing (1). Large numbers of patients face lengthy waits for TKR, especially since the start of the COVID-19 pandemic (2). During their wait, patients typically experience severe pain and difficulty with daily activities (2). Even after TKR, around 10–20% of patients report poor outcomes, such as persistent pain or dissatisfaction (3-5).

Numerous predictors of poor post-TKR outcomes have been identified, including worse pre-operative pain and function, low musculoskeletal health literacy, and unfulfilled outcome

expectations (6-8). Pre-operative TKR interventions can potentially modify these predictors. Pre-operative TKR education is particularly important for setting realistic expectations and supporting patients to actively engage in their care (9, 10). There is also growing evidence that prehabilitation (health/wellbeing optimisation) interventions may improve patient outcomes pre- and post-TKR (11-13). Despite this, current United Kingdom (UK) National Health Service (NHS) pre-operative TKR intervention provision is variable, inefficient, and often inadequate (14, 15). When provided, pre-operative TKR support has traditionally been delivered via face-to-face group classes, often called *'knee schools'* (14, 16). These present various limitations. For example, they are time-consuming to deliver, and patients may not remember the information provided (9, 17).

Delivering pre-operative TKR support via a digital intervention could help address these limitations and aligns with the NHS's focus on digital transformation (18, 19). Preliminary evidence suggests TKR digital interventions may improve patient outcomes and be cost-effective (20). However, digital interventions also have many potential drawbacks. For example, engagement with digital interventions is often low and varies between different patient subgroups; this can limit their effectiveness and risks increasing health inequities (21, 22). Rigorously developing digital interventions is essential to mitigate these drawbacks. Despite this, a recent review of educational joint replacement digital interventions reported none had been developed using a validated framework or co-designed with the intended users (23). Other reviews have raised concerns about the quality of TKR apps and YouTube videos, and the readability of online TKR educational resources (24-26).

To help address the above issues, this project aimed to develop a novel UK-based pre-operative TKR education and prehabilitation digital intervention, the *'Virtual Knee School'* (VKS) (27). Figure 1 provides the objective of each project phase. In line with current guidance (28), this paper comprehensively reports the VKS development process. Phases

1–2 are reported elsewhere (29, 30), so this paper focuses on the overall project and Phases 3–4.

Figure 1

Methods

Design

The VKS was developed using an evidence-, theory- and person-based approach. This involved drawing on the Medical Research Council (MRC) framework for developing and evaluating complex interventions (31) and the person-based approach (PBA) (32). The MRC framework was chosen because it provides well-established, flexible guidance (31). The PBA was identified as a valuable complementary approach as it provides more detailed guidance on intervention development actions (32). Furthermore, it focuses on understanding the intended users' psychosocial contexts and perspectives, with the aim of ensuring interventions are acceptable and engaging for users (32). This was considered particularly important because the VKS was designed to be used without health professional support. The PBA's core elements include iterative qualitative/mixed methods research and the creation of *'guiding principles'* (summary of the key intervention design objectives and features) (32, 33).

A mixed methods design with four phases was employed (Figure 1). The design was considered using the typology of Creswell and Plano Clark (34), who describe three *'core'* mixed methods designs. These can be used in isolation or intersected with other approaches to form a *'complex'* design. This project's design was considered complex as it involved multiple phases and each empirical phase had a qualitative or mixed methods design. The project's intent most closely aligns with that of an *'exploratory sequential'* core design, which involves using qualitative data to inform a novel *'quantitative feature'* (e.g. an intervention or

instrument), which is then quantitatively evaluated. A process evaluation of the VKS was initially planned but could not be conducted due to factors such as the COVID-19 pandemic and large volume of content included in the VKS. The project's overarching design was still considered exploratory sequential, which helped to ensure that validity concerns associated with the exploratory sequential design were identified and addressed. For example, to demonstrate that the qualitative/mixed methods findings informed the quantitative feature, the findings of the intervention planning phases were explicitly linked to the VKS features.

Each phase was given equal priority, conducted largely sequentially, and informed by the preceding phase(s). Correspondingly, all the phases involved integration through building (35). Additionally, all the phases' findings were integrated to generate *'meta-inferences'*. Meta-inferences provide a more complete understanding of a topic than the inferences of the separate strands of a mixed methods study, as they are overall conclusions developed by integrating findings from the separate strands (36). Generating the meta-inferences involved linking inferences from the different phases; assessing potential similarities/differences; developing credible explanations of the similarities/differences; and identifying implications of the findings (36). Consistent with the mixed methods design, the project was primarily underpinned by pragmatism (34).

Ethical approval, registration, and reporting

Ethical approval for Phase 1b and Phases 2–4 was gained from the XXX (XXX) and XXX (XXX) respectively. All participants provided electronic informed consent prior to participating. ISRCTN registration of the overall project was obtained on 24th April 2020 (XX). The primary reporting guideline used for this paper was the GUIDance for the rEporting of intervention Development (GUIDED) checklist (28).

Research team and oversight

This project was led by a female physiotherapist (XX) during her full-time Clinical Doctoral Research Fellowship. Prior to the project, she had gained relevant skills through her clinical/academic work (e.g. interviewing skills) but had not conducted an intervention development project. Other team members have expertise in multiple relevant areas including orthopaedics, qualitative/mixed methods research, and digital behaviour change intervention development.

The project was overseen by a Project Advisory Group (PAG) which included an independent chair, a local collaborator, the lead researcher, three of her supervisors, and three Patient and Public Involvement (PPI) representatives (one of whom was recruited halfway through the project to improve the group's ethnic diversity). The PAG contributed to multiple activities such as defining the project success criteria and monitoring the project progress. The PAG met approximately every six months throughout the 39-month project. Additional meetings with specific members were organised when required.

Patient and Public Involvement (PPI)

PPI was central throughout the project with the aim of ensuring the research procedures and VKS were acceptable and inclusive, and the findings were effectively disseminated (Table 1).

Table 1

Virtual Knee School prototype planning (Phases 1–3)

Three intervention planning phases were conducted (Figure 1). Phases 1–2 are reported elsewhere (29, 30), so are not detailed here.

Theoretical modelling (Phase 3)

Phase 3 involved using the following three theoretical modelling approaches to help guide the VKS design, description, and evaluation:

1. Creating guiding principles
2. Undertaking a behavioural analysis
3. Developing a logic model.

All three approaches were implemented by the lead researcher. The findings were then refined through discussions with other research team members. Further details of each theoretical modelling approach are provided below.

1. Creating guiding principles

In line with the PBA (32), guiding principles were created with the aim of ensuring the VKS has a coherent focus and is acceptable and engaging for users. This involved specifying what the VKS aims to provide (outcome objective) and the behaviours it seeks to change (behavioural objective). The objectives were primarily based on the project planning PPI consultations and pre-operative TKR intervention literature. Next, groups of considerations related to the intended VKS users' characteristics, contexts and needs were identified from the project planning PPI consultations and Phase 1–2 findings. Considerations that could not be addressed through a fully automated digital intervention (e.g. direct social support) were excluded. Each group of considerations was used to develop a VKS guiding principle. The VKS guiding principles were designed to be complementary to the PBA common guiding principles (principles proposed to optimise engagement with most digital behaviour change interventions) (32).

2. Undertaking a behavioural analysis

A behavioural analysis was undertaken to systematically analyse each behaviour targeted by the VKS, code potential VKS features using standardised terminology, and map the features to the project planning PPI consultations and Phase 1–2 findings. The behavioural analysis was conducted using the Behaviour Change Wheel (BCW), a theoretical framework underpinned by the Capability, Opportunity, Motivation, Behaviour (COM-B) model of behaviour (37). The BCW was primarily chosen because it is comprehensive, relatively simple, and well-established; addresses context; and is linked to the Behaviour Change Technique Taxonomy v1 (BCTTv1), a well-established taxonomy of 93 behaviour change techniques (BCTs) (38).

The behavioural analysis methods were based on previous relevant studies (39-41). Firstly, behavioural analysis tables were created for each of the VKS's target behaviours. To populate the tables, sets of barriers and facilitators to the target behaviour and potential VKS features that could address the barriers and facilitators were identified from the project planning PPI consultations and Phase 1–2 findings. Extra features were added based on research team discussions. All the features were mapped to COM-B model components, BCW intervention functions, and BCTTv1 BCTs.

To check for additional potentially important behavioural targets/intervention components, the behavioural analysis tables were compared to the BCW, BCTTv1, and BCTs identified in a systematic review of digital-based osteoarthritis self-management programmes by Safari et al. (42). The behavioural analysis tables were also compared with the VKS guiding principles to check for inconsistencies.

3. Developing a logic model

A process-orientated logic model was developed to provide a diagrammatic representation of the VKS, including its proposed causal mechanisms and intended outcomes (43). This process was informed by the MRC process evaluation guidance (44), other digital intervention logic models (39-41), and Type 4 logic model guidance (45). The logic model content was based on the project planning PPI consultations, Phase 1–2 findings, additional Phase 3 findings, pre-operative TKR intervention literature, and digital intervention literature.

Virtual Knee School prototype development and refinement (Phase 4)

Phase 4 involved developing a VKS prototype and iteratively refining it by evaluating how patients used it and exploring their perspectives of it.

Virtual Knee School prototype development

Intervention features selection

In line with PBA guidance (46), intervention planning tables were created to collate potential VKS features and document the rationale and priority of each feature. The features were prioritised using the '*Must have, Should have, Could have, Would like*' (MoSCoW) model (47, 48) based on criteria developed by the research team (Table 2). Separate intervention planning tables were created for each proposed VKS section (Supplementary File 1).

Table 2

All *'Must have'* and *'Should have'* features, some *'Could have'* features and no *'Would like'* features were included. The selection of *'Could have'* features was primarily based on consensus within the research team on how important each feature was perceived to be and the time required to develop it.

Content development

The content was drafted by the lead researcher and informed by research team discussions and PAG PPI member consultations. Sources used to inform the content included the Phase 1–3 findings, additional relevant research, other digital interventions research team members had helped develop, relevant guidelines (14, 49-55), publicly available information from respected sources (56-62), and XX orthopaedic education resources. The exercise programme was designed using a multi-step process (Supplementary File 1). Key priorities during the content development included addressing the VKS and common guiding principles and promoting accessibility/inclusion.

Prototype design, build and testing

A web design/development company called XX was commissioned to create and host the VKS prototype (63). This involved a multistage design, build and testing process informed by XX's well-established procedures (Table 3).

Table 3

Virtual Knee School prototype evaluation and refinement

Overview

A think-aloud study was undertaken to evaluate the VKS prototype's usability, explore patients' perspectives of it, and prioritise and implement changes to it. The think-aloud method was chosen because it allows users' immediate responses to an intervention to be observed/explored, enabling important content and navigational issues to be addressed prior to evaluating the intervention in real-world settings (32, 47). Multiple strategies were employed to ensure trustworthiness. For example, an audit trail was maintained and the lead researcher kept a reflexive journal.

Participants

Patients were recruited from an NHS teaching hospital by posting recruitment packs to patients and discussing the study with patients at orthopaedic and pre-assessment clinics. Patients who heard about the study via word of mouth were also included. Additional recruitment activities were employed with the aim of facilitating the recruitment of patients who were male and/or from a Black, Asian, or other minority ethnic group (Supplementary File 1). None of the additional activities led to the recruitment of any participants.

Adults able to give informed consent were eligible for inclusion if they were:

- able to communicate in English;
- listed for primary TKR at a UK hospital and/or had undergone primary TKR at a UK hospital within the past two years;
- able to use and had access to the Internet and email and/or were willing and able to be interviewed in person.

To help ensure the VKS meets the needs of diverse patients, maximum variation purposive sampling was employed based on age, gender, ethnicity, highest educational qualification completed, varying experience of TKR, and varying confidence in using the Internet (64).

Nine participants were interviewed as analysis of the eighth and ninth participants' interviews did not suggest any substantial changes should be made to the VKS prototype, suggesting the sample size was sufficient (65). Seven participants were patients at the hospital where the lead researcher was based but none had received care from the lead researcher or any other research team member prior to the study.

Data collection

The lead researcher undertook the data collection independently between 13th October 2021 and 20th January 2022. All participants were invited to participate in two concurrent think-aloud interviews (66, 67). To meet COVID-19 guidance, participants were encouraged to participate remotely via Microsoft Teams but could participate in person if necessary (e.g. if they lacked internet access). All four participants who requested in-person interviews chose to be interviewed in their own home. All the participants were aware that the lead researcher's PhD was focused on developing the VKS, which may have encouraged them to provide socially desirable feedback (65). To help address this, the researcher emphasised that negative comments would be particularly valuable for refining the VKS prototype.

Each interview was guided by a topic guide (Supplementary File 1). To ensure sufficiently detailed information was obtained, an interactive think-aloud interview style was employed (68, 69). This involved the researcher instructing the participant to work through the VKS prototype whilst speaking their thoughts out loud, asking them probing questions, and directing them to specific pages/aspects when appropriate. Additionally, the researcher asked brief semi-structured questions towards the end of each interview to explore the participant's perspectives of the prototype overall. To the lead researcher's knowledge, all the participants were alone during their interviews. One participant's health problems made it difficult/painful for her to use a digital device, so the lead researcher performed the manual actions required to navigate the prototype for this participant in line with her directions.

All the interviews were video- and audio-recorded except for one in-person interview, which was not video-recorded due to an error. The lead researcher documented field notes during and/or shortly after each interview. Interviews lasted between 23 and 87 minutes (median 63 minutes; interquartile range 17 minutes) and were transcribed intelligent verbatim by a professional transcription company.

406 *Data analysis*

407 Data were analysed using the approach described by Bradbury et al. (65), which facilitates
408 efficient systematic analysis of qualitative data during intervention refinement studies. This
409 involved the lead researcher working through each transcript line by line to identify positive
410 and negative comments about the VKS prototype. Changes that could be made to address
411 each negative comment were identified and prioritised. The prioritisation was undertaken
412 using the MoSCoW model (47, 48) based on criteria adapted from Bradbury et al. (65) and
413 the other PBA resources (70, 71) (Table 4). The research team discussed the potential
414 changes and agreed which changes to implement.

415

416 Table 4

417

418 The analysis was documented in a *'table of changes'* in Microsoft Excel (72) (Supplementary
419 File 1). Comments were also coded using QSR International NVivo software (Version 12 and
420 Release 1) to ensure verbatim comments were readily accessible.

421

422 The data analysis and implementation of changes were conducted concurrently with the data
423 collection to enable the impact of changes made based on earlier interviews to be explored
424 in subsequent interviews (32). Member checking was not employed due to the rapid iterative
425 nature of the analysis.

426

427 ## Results

428 **Virtual Knee School prototype planning (Phases 1–3)**

429 The Phase 1–2 findings are reported elsewhere (29, 30), so only the Phase 3 findings are
430 detailed below.

431

Theoretical modelling (Phase 3)

1. Creating guiding principles

The following VKS objectives were specified.

- Outcome objective: to provide a patient-centred, widely accessible, and cost-effective pre-operative TKR education and prehabilitation resource.
- Behavioural objective: to support patients listed for primary TKR to engage with pre-operative TKR care in a web-based format, pre-operative TKR education, a pre-operative TKR exercise programme and healthy lifestyle changes.

Six groups of considerations related to the intended VKS users' characteristics, context and needs were identified (Supplementary File 2), each of which informed a VKS guiding principle (Table 5).

Table 5

2. Undertaking a behavioural analysis

Supplementary File 2 provides the behavioural analysis tables. The potential VKS features targeted all six COM-B model components and employed six BCW intervention functions (education, persuasion, training, environmental restructuring, modelling, and enablement). The BCW intervention functions not employed (incentivisation, coercion, and restrictions) involve creating an expectation of external consequences or imposing external rules, which may reduce intrinsic motivation (73, 74), so were not considered appropriate for the VKS.

The potential VKS features employed 25 BCTs. Fourteen additional BCTs were identified from the systematic review by Safari et al. (42) (Supplementary File 2). Comparison of the behavioural analysis tables with these 14 BCTs and the BCTTv1 did not lead to inclusion of any extra BCTs. This was mainly because the behavioural analysis tables already included

numerous BCTs identified through a rigorous process, so implementing these BCTs well was considered more of a priority than adding extra BCTs, which are likely to have been less contextually relevant.

No major inconsistencies between the behavioural analysis tables and VKS guiding principles were identified. However, the healthy lifestyle change behavioural analysis table was particularly extensive. Adding extra healthy lifestyle change-related features to the VKS guiding principles to account for that was decided against to help ensure the VKS was not too complex/overwhelming for users.

3. Developing a logic model

Figure 2 provides the VKS logic model. As this shows, the VKS aims to help address variations, inefficiencies, and inadequacies in current pre-operative TKR intervention provision. The key VKS features target all the COM-B model components except for automatic motivation. The intended patient responses to the VKS are proposed to dynamically interact with the VKS mediators. Some patients may be unable to access/effectively engage with websites; therefore, the key unintended consequence to avoid is increasing health inequities. The VKS mediators are proposed to improve numerous pre- and post-operative patient outcomes. Various contextual moderators may affect the patient outcomes both directly and indirectly by influencing the VKS's proposed causal mechanisms.

Figure 2

Virtual Knee School prototype development and refinement (Phase 4)

Virtual Knee School prototype summary

Figure 3 and Supplementary File 3 summarise the initial VKS prototype. A hybrid information architecture was employed. On their first login, users were tunnelled to the introductory section menu to help ensure they viewed a welcome video aimed at addressing key barriers to engagement with the VKS and its target behaviours. Users could then access the remaining sections in any order.

Figure 3

To account for users' varying preferences and needs, two tailoring strategies were employed.

1. Computer-tailoring: this involves using computer algorithms to adapt an intervention's content/delivery to the individual user (75, 76). The key application of computer-tailoring in the VKS prototype was in the goal-setting feature, which provided personalised feedback based on the user's goal attainment.
2. Self-tailoring: this involves offering choices so the user can adapt the intervention's content/delivery themselves (77). Multiple self-tailoring strategies were employed in the VKS prototype. For example, the accessibility toolbar enabled users to change the language, text size and contrast; and the goal-setting feature included the option to set a personal exercise goal.

Virtual Knee School prototype evaluation and refinement

The lead researcher approached 29 patients via the NHS teaching hospital and was contacted by six additional patients. Of these 35 patients, 24 were screened, 10 were invited to participate, and nine consented. Two participants withdrew after their first interview due to increased anxiety or serious health problems. Supplementary File 3 provides the participant

flow chart and participants' characteristics. The relevant participant's pseudonym, age group, experience of TKR, and confidence in using the Internet is provided for each illustrative quote.

Participants' overall views of the Virtual Knee School prototype

Most participants were positive about the VKS prototype overall, making comments such as *"I think it's an absolutely invaluable tool"*. Key reported benefits included that it is comprehensive, realistic, and reassuring; and would provide a constantly available resource to refer back to. One participant felt viewing the VKS before being listed for TKR would have facilitated her decision-making and helped her identify questions to ask her consultant. Furthermore, three participants commented they would have liked to access the prototype pre- and post-operatively:

> "And I would have loved, if I had been lying in bed afterwards, it would have been great to just be able to look up anything I thought about." (Arthur, 80–89, post-TKR, very confident)

Feedback about the variety of exercises, accordions and patient stories was particularly positive. Participants were also very complimentary about the *"perfectly great videos"*, valuing aspects such as their clarity and the option to add subtitles in other languages. Three participants specifically highlighted that the exercise videos were easier to follow than static images:

> "It's nice to have all the exercises videoed out, rather than just a diagram showing you where to move your hand next or where to move your leg next because I don't think they're very constructive a thing. Seeing videos like this is more beneficial." (Ella, 40–49, pre-TKR, confident)

Participants generally felt the accessibility toolbar was useful, and a few emphasised they liked the *"simple language"*. Most participants also thought the website was clear and simple to use, even for people with lower digital literacy:

> "I liked the website, how it was organised. And it was very visual. Then if you're not very computer literate it's very practical." (Jessica, 50–59, pre-TKR, neither confident nor unconfident)

In contrast, both participants who were unconfident in using the Internet felt the digital format did not meet their needs, as they found it anxiety provoking and/or too difficult to use:

> "[...] to me a website is alright if you can use these, but if you can't use them, it's just not helpful at all." (Vera, 70–79, post-TKR, unconfident)

Both these and other participants emphasised the importance of providing support via alternative formats such as face-to-face care, a video, or a booklet. Correspondingly, all four participants who viewed the Portable Document Format (PDF) exercise booklet felt it was valuable:

> "I think that [exercise booklet]'s really good because I think, again, thinking about accessibility and people not having full-time access to the Internet or laptop or whatever." (Naomi, 60–69, post-TKR, very confident)

One participant who was confident in using the Internet also felt the VKS prototype did not meet his needs. This was mainly because he knew most of the information already and perceived the exercise programme as too easy. The latter appeared to be at least partly because he had ready access to a swimming pool, so was used to exercising in water. This

participant also disliked the instructions on aspects such as how to use the website and play a video, which he found *"a bit babyish"* and unnecessary:

> "[…] but it's just a bit, making me feel like, ooh, blooming heck, more load of rubbish, you know, I don't need all this." (Laurence, 60–69, pre-TKR, confident)

Conversely, other participants provided positive feedback about the instructions. Conflicting feedback was also obtained about other content/features. For example, some participants felt the goal-setting feature would support them to engage with the exercise programme. Reasons for this included that it would provide a focus and *"something to kind of measure yourself against"*. Many participants particularly liked the personalised feedback as they considered it encouraging, constructive and specific. In contrast, a few participants did not think they would use the goal-setting feature. This appeared to be because they were already confident in their ability to adhere to their exercise programme. One participant also suggested that an individual's personality would influence whether they used the goal-setting feature:

> "I think a lot of it's down to your personality, to be quite honest. I think there are people that would welcome it and think it's absolutely brilliant. There are other people that would think, well, I can't be bothered […]" (Glen, 70–79, post-TKR, confident)

Participants' opinions were also divided over the sign-up/login process. Although many participants found the process easy, others found it difficult or required assistance to complete it. Additionally, some participants raised broader concerns about signing up, such as a fear of being sent lots of messages. Correspondingly, a few participants felt at least some of the VKS should be freely accessible without the need to sign-up:

> "I think you should [make most of the VKS freely accessible], especially for… Most of the people will be older people who are not very computer literate and having to put passwords in, understanding lowercase and uppercase and with their stubbly arthritic fingers, like myself, they seem to go everywhere." (Haaniya, 60–69, pre- and post-TKR, neither confident nor unconfident)

In contrast, other participants were quite happy with the idea of signing-up or even preferred it, for example due to feeling it would enable them to receive more personalised content.

Refinements to the Virtual Knee School prototype

Multiple potential changes to the VKS prototype were identified, prioritised, and implemented when appropriate (Table 6).

Table 6

Two of the most substantial changes involved amending the VKS prototype's information architecture. Firstly, the tunnelling to the introductory section menu was removed because two of the four participants who trialled it found it unhelpful/confusing. One participant related this to the relatively large volume of text on the introductory menu, which she felt could be *"off-putting"*. The other participant felt all websites should open at the homepage because *"that's the starting point"*. The second major information architecture change was primarily made in response to comments about the education dropdown menu. This displayed the titles of all 24 education pages/subpages, making the volume of content seem overwhelming:

> "When you see all these sections, you think it's going to be a mammoth, but I like the fact that it's short, it's straight to the point." (Ella, 40–49, pre-TKR, confident)

This was addressed by removing the education menu page and promoting the education subsections to full sections. Each education section then had a separate dropdown menu, limiting the number of page titles displayed to a maximum of eight.

Most other changes were more minor adaptions to the design or content. For example, '*pre-op'* was added to the exercise section title to help avoid confusion about the exercise programme timing. Subsequent feedback suggested this change was successful:

> "[…] because you've put pre-op exercise plan, it is made clear it's pre-op, not post-op." (Jessica, 50–59, pre-TKR, neither confident nor unconfident)

Examples of issues that were not fully resolved

Whilst most changes appeared to be successful, some issues were not fully resolved. For example, after amending the accessibility toolbar instructions and header for clarity, one participant still felt the accessibility toolbar was too complex for her:

> "Well, it is good for people who are very literate, fluent in computer and anything it's alright, but I'm at the creeping stage. […] I'm still bottle fed." (Zuri, 70–79, pre- and post-TKR, unconfident)

A few issues were not fully resolved because participants missed extra text that had been added. There were also some issues that were not addressed to avoid contradicting other priorities/feedback. For example, one participant felt patients may not have time/be able to make lifestyle changes pre-operatively, so was concerned the healthy lifestyle information may risk *"setting you up to fail"*. Removing the healthy lifestyle information to address this

would have been inconsistent with VKS guiding principle six. Furthermore, other participants felt the healthy lifestyle guidance was valuable:

> "It's all good general stuff that relates specifically to the operation but has much wider implications." (Glen, 70–79, post-TKR, confident)

Meta-inferences

Two intersecting meta-inferences were generated, each of which is underpinned by three principles and provides a recommendation for clinical practice and future research (Figure 4). A brief overview of the rationale for each meta-inference is provided below.

Figure 4

Meta-inference 1: Comprehensive pre-operative TKR education and prehabilitation support should be rapidly accessible in digital and non-digital formats

This project's findings suggest patients and health professionals generally perceive comprehensive pre-operative TKR support as valuable, but there is a risk of overwhelming patients with too much information. Delivering information appropriately appears key to addressing this risk. For example, Phase 4 participants felt the accordions were useful for reducing the volume of text displayed on the VKS prototype. Another important finding was that digital interventions offer multiple potential benefits in the pre-operative TKR context. A range of potential benefits were identified across all the project phases. These included increasing service efficiency, providing tailored support, allowing rapid information provision, and providing a constantly available resource to refer back to. Benefits of specific digital features were also identified, such as exercise videos being easier to follow than static images. Conversely, it was evident throughout this project that digital interventions are unable to fully cater for all patients' needs and preferences. For example, some patients find digital interventions difficult to use and anxiety provoking, or simply prefer paper-based

alternatives. Providing support in both digital and non-digital formats is therefore recommended.

Meta-inference 2: Pre-operative TKR digital interventions should employ computer- and self-tailoring to account for patients' individual needs and preferences

Meta-inference 2 focuses on digital intervention tailoring. It therefore intersects with Meta-inference 1, which highlights a potential benefit of digital interventions is that they can provide tailored support. The importance of tailoring pre-operative TKR interventions to patients' individual needs and preferences was emphasised throughout this project. For example, the VKS guiding principles state the VKS education and exercise programme should account for users' varying preferences and needs/circumstances. To help address this, computer- and self-tailoring strategies were employed in the VKS prototype. Some Phase 4 participants particularly liked the VKS goal-setting feature, supporting the use of computer-tailoring for providing personalised feedback. Phase 4 participants also provided positive comments about features such as the accessibility toolbar, highlighting the value of self-tailoring strategies. Another key benefit of self-tailoring strategies is that they do not rely on users logging in, unlike many computer-tailoring strategies.

Discussion

This paper reports how a *'Virtual Knee School'* (VKS) digital intervention for patients awaiting TKR was systematically developed using an evidence-, theory- and person-based approach. The findings of three intervention planning phases were combined with numerous PPI activities to create a VKS prototype. Evaluating how patients used the prototype and exploring their perspectives of it enabled key usability problems and broader concerns about the prototype to be identified. Most of these were successfully addressed. Many participants considered the VKS a valuable resource, but a minority felt its digital format or content or did not meet their individual needs. Integrating the findings of all the project phases generated

two meta-inferences, each of which provides a recommendation on pre-operative TKR care for clinical practice and future research.

The diversity of feedback obtained about the acceptability of the VKS prototype is a key finding of this project. Acceptability is a broad concept, encompassing components such as perceived effectiveness, usability, and burden (78). Most participants appeared to find the VKS prototype acceptable overall because they valued its content and considered it relatively easy to use. Conversely, three participants felt the prototype's acceptability was low in their specific context. For one participant, this appeared to relate mainly to the prototype's perceived effectiveness, as he thought its content was too basic. Arguably, this does not present a major concern for the potential value of the VKS as this individual had already obtained and acted on relevant health information, suggesting he had high health literacy. Ensuring the VKS is appropriate for individuals with low health literacy is more of a priority because low musculoskeletal health literacy is associated with worse outcomes post-TKR (7), and digital interventions have the potential to improve health literacy (23).

The other two participants who perceived the VKS as less acceptable related this to the digital delivery format, which they found anxiety provoking and/or too difficult to use. This demonstrates that digital interventions are unlikely to meet all patients' needs, even when their development involves extensive patient input and prioritises accessibility/inclusion. This is a major concern for health equity, as patients at risk of digital exclusion often have the greatest health needs (22). One option to address this would be to employ digital inclusion strategies, such as signposting patients who are given a digital health intervention to third sector digital skills training programmes. This may be particularly valuable because gaining digital skills is likely to have positive effects on other areas of patients' lives (22). As participants in this project highlighted, it is also essential to offer non-digital formats to account for patients who remain unable/unwilling to use digital interventions.

Usability incorporates the effectiveness, efficiency and satisfaction with which users can achieve their objectives when using an intervention (79). Many of the VKS prototype's initial usability problems were linked to efficiency and satisfaction. For example, a couple of participants found the tunnelling to the introductory section unhelpful/confusing, but it did not prevent them navigating the prototype. There were also instances where participants were unable to achieve their objectives effectively. Most notably, a few participants could not complete the sign-up/login process independently. Some participants also raised broader concerns about signing up, such as a fear of being sent lots of messages. Similar issues have been highlighted in previous research (80), and could be addressed by making some of the intervention content freely accessible without the need to sign up. This approach could feasibly be implemented in clinical practice. However, it could pose problems from an evaluation perspective. For example, control group participants could potentially access the freely accessible content, increasing the risk of contamination bias (81).

This project builds on previous studies demonstrating the value of using an evidence-, theory- and person-based approach to develop digital interventions (39-41). There are some notable similarities between this project's findings and those of previous studies. For example, when refining their digital intervention for cancer survivors, Bradbury et al. (41) made the names of buttons to the intervention sections more descriptive to help avoid confusion. Similarly, the VKS exercise section title was amended to include *'pre-op'*. This emphasises the importance of ensuring that digital intervention content is self-evident or at least self-explanatory (82). This project expands on previous evidence-, theory- and person-based approach intervention development studies by demonstrating how aspects of the approach can be adapted. For example, this project involved developing bespoke criteria for prioritising potential features and prototype changes (Table 2; Table 4).

Strengths and limitations

The systematic and transparent approach used to develop the VKS is a key strength of this project. Furthermore, generating meta-inferences provided greater insights than would have been gained by considering each phase in isolation. The central role of PPI was another strength. By being involved in multiple activities, the PAG PPI members developed a thorough understanding of the project and provided highly valuable input. This complemented the qualitative research, which involved patients who were unfamiliar with the project and hence offered *'fresh'* perspectives (83).

Only including three PPI members in the PAG limited the group's diversity. Similarly, there were some limitations with the diversity of the think-aloud interview sample. Diversity was obtained in key characteristics, such as age, confidence in using the Internet, and educational level (Supplementary File 3). Some ethnic diversity was obtained, but only patients able to communicate in English were eligible. Furthermore, few participants had a disability or health condition that could affect their ability to use a website or carry out gentle exercises, so it was not possible to comprehensively explore the accessibility of the VKS. Additional limitations of this project were that all the phases relied on some subjective judgements (e.g. during the data analysis), and participants did not have the opportunity to try using the VKS prototype independently or implementing the intended health behaviour changes.

Implications for practice and future research

Both meta-inferences generated in this project provide a recommendation for clinical practice and future research. The first recommendation states comprehensive pre-operative TKR education and prehabilitation support should be rapidly accessible in digital and non-digital formats. The project's findings highlight strategies for addressing this, such as ensuring that all sections of digital interventions are rapidly accessible and providing pre-

operative TKR support via a booklet. Future research focused on identifying how to optimise the implementation of pre-operative TKR care in digital and non-digital formats would be valuable. As discussed above, this could include incorporating digital inclusion strategies.

The second recommendation suggests pre-operative TKR digital interventions should employ computer- and self-tailoring to account for patients' individual needs and preferences. Complementary benefits of these tailoring strategies were identified and suggest it would be helpful to employ the following.

1. Self-tailoring strategies in isolation to deliver freely accessible content.
   This could include offering features such as an accessibility toolbar (for changing the language, text size and contrast) and accordions (for providing optional extra text); providing a flexible exercise programme with a choice of different exercises; and delivering content using more than one format (e.g. exercise videos and a PDF exercise booklet).
2. Computer-tailoring strategies, combined with self-tailoring strategies where appropriate, to deliver features that provide personalised feedback.
   This could include providing a goal-setting feature that offers a choice of goals and provides personalised feedback based on the user's goal attainment. It could also include providing healthy lifestyle screening features, such as an alcohol consumption screening feature that provides personalised feedback about whether the user is meeting low risk drinking guidelines. This study's findings highlight the importance of ensuring that any feedback provided is encouraging, constructive and specific.

Future research of pre-operative TKR digital interventions could explore other computer-tailoring strategies, such as tailoring the message frame to patients' information processing styles (76).

Overall, this project's findings suggest the VKS is a potentially valuable resource and warrants further research. Conducting a randomised feasibility study to determine if/how to progress to a randomised controlled trial (RCT) would be a logical next step. Pursuing this option would be a lengthy process. This presents a tension with PAG members' feedback, which suggested the priority should be to rapidly implement the VKS. In light of this feedback and the limitations of RCTs, considering alternative evaluation options is warranted. For example, conducting a realist evaluation could be valuable for exploring how the VKS works/does not work for specific groups of patients in specific contexts (84). Given the concerns about digital exclusion highlighted above, and the intersection of digital exclusion with other social determinants of health (22), it is a priority to ensure that any future research into the VKS explores its impact on health inequities.

Conclusions

This project systematically integrated evidence, theory, and stakeholders' perspectives to develop a novel pre-operative TKR education and prehabilitation digital intervention, the *'Virtual Knee School'* (VKS). The central role of PPI throughout the project helped to optimise the acceptability and inclusivity of the research procedures and VKS prototype. Feedback from diverse participants enabled the prototype to be iteratively refined. The findings suggest the VKS is a promising resource, but its digital format is unlikely to meet all patients' individual needs. Future research of the VKS is therefore warranted and should include exploring its impact on health inequities. Integrating the findings of all the project phases emphasised the importance of providing comprehensive, rapidly accessible pre-operative TKR support in digital and non-digital formats; and suggested that pre-operative TKR digital interventions should employ computer- and self-tailoring to account for patients' individual needs and preferences.

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Figure legends

Figure 1: Project flow chart

Flow chart showing the design and objective of each project phase, and how the phases link to each other and future work. Arrows at the bottom of the flow chart demonstrate Patient and Public Involvement (PPI) was central throughout the project, and PPI is anticipated to be central during any future related work.

Abbreviations: pre-op, pre-operative; TKR, total knee replacement; VKS, Virtual Knee School

Figure 2: Virtual Knee School logic model

Logic model of the Virtual Knee School (VKS), including the problems it seeks to address, its main objectives, its key features and intervention processes, its proposed causal mechanisms, the intended patient outcomes, and contextual moderators. To avoid overcrowding and ensure legibility, relationships between factors in different columns of the logic model are not shown.

Abbreviations: post-op, post-operative; pre-op, pre-operative; psych, psychological; TKR, total knee replacement; VKS, Virtual Knee School

Figure 3: Virtual Knee School prototype information architecture summary

Summary of the Virtual Knee School (VKS) prototype information architecture, showing the five website sections and three page levels.

[a] The main section also included the following pages accessible via the header, footer or meganav (expandable menu): Help; Accessibility statement; Privacy and cookies policy; Other helpful websites; Contact us.

[b] Users were tunnelled to the introductory section menu on their first login but not subsequent logins.

Figure 4: Meta-inferences schematic diagram

Summary of the meta-inferences generated by integrating the findings of all the project phases. The three principles underpinning each meta-inference, and the intersection between the two meta-inferences, are included.

Abbreviations: pre-op, pre-operative; TKR, total knee replacement

Development of a Virtual Knee School tables

Table 1: Patient and Public Involvement overview

Activity	Description	Example of impact
Project planning consultations	Seven NIHR XX BRC PPI representatives joined a general consultation, which involved discussing pre-operative TKR care. Two NIHR XX BRC PPI representatives joined a more focused consultation, which involved reviewing an existing digital intervention for people with joint pain.	The VKS was developed as a website (rather than a mobile application) to help maximise accessibility.
PAG meetings and follow-up	Three PAG PPI members provided oversight of the project by attending PAG meetings and contributing to follow-up activities as required.	The Phase 4 recruitment procedures were amended to include a PAG PPI member sharing a WhatsApp recruitment message with contacts in her communities.
Reviewing documents	Two PAG PPI members and seven NIHR XX BRC PPI representatives reviewed the Phase 1b participant documents. Three PAG PPI members reviewed the Phase 2 and/or 4 participant documents and topic guides.	Bold 18pt text was added to the top of the Phase 2 and 4 Participant Information Sheets to explain how to request the document in large print.
Survey pilot testing	Two PAG PPI members and one additional PPI representative pilot tested the Round 1 survey in the Phase 1b Delphi study.	Explanations of the roles of different health professional teams were added.
Consultations on the VKS content and exercise programme	Two PAG PPI members participated in consultations about the VKS content and exercise programme design.	Extra details were added to the educational video transcripts e.g. about sleep difficulties and psychological well-being.
Consultations and coproduction activities during the VKS prototype design, build and testing	Three PAG PPI members contributed to creating a provisional VKS template and style guide; creating the VKS designs; informing the VKS prototype build; and/or formal UAT. Two additional PPI representatives contributed to informal UAT.	Instructions on how to use the accessibility toolbar were added to the *'About the Virtual Knee School'* and *'Help'* webpages.
Filming to create VKS videos	Eight volunteer patient models were filmed to create the VKS education and exercise videos.	The VKS videos were positively evaluated by participants in Phase 4.
Dissemination of the project findings	Three PAG PPI members reviewed plain English summaries and an infographic of the project findings. Two PAG PPI members contributed to a public dissemination event, which included helping to plan the event and presenting at the event.	PPI input was weaved throughout the dissemination event presentation, rather than being limited to a section on PPI.

Abbreviations: BRC, Biomedical Research Centre; NIHR, National Institute for Health and Care Research; PAG, Project Advisory Group; PPI, Patient and Public Involvement; UAT, user acceptance testing; VKS, Virtual Knee School

Table 2: Prioritisation criteria for including features in the Virtual Knee School prototype

Code	Reason for inclusion[a]	Importance level	Time-consuming to develop[b]	Priority[c]
FN	Important for the VKS functioning/navigation.	1	No	Must have
S	Required for safety purposes.		Yes	Must have
R	Required to meet relevant regulations/guidelines.			
VGP (VGP number)	Required to meet one or more VGPs developed in Phase 3.			
CGP (CGP number)	Required to meet one or more person-based approach CGPs (1).	2	No	Should have
PPI	Addresses PAG PPI member feedback.		Yes	Could have
PAS	Addresses BSI PAS 277:2015 quality criteria (2).			
NICE	Addresses the NICE primary joint replacement guideline (3).			
VIR (item number)	Addresses one or more items prioritised as *'Very important'* in the Phase 1b modified Delphi study final recommendations (4).			
IR (item number)	Addresses one or more items prioritised as *'Important'* in the Phase 1b modified Delphi study recommendations (4).	3	No	Could have
			Yes	Would like
BF (barrier/ facilitator set[d])	Addresses one or more barriers/facilitators identified in the Phase 3 behavioural analysis.			

[a] Key findings from the Phase 1a rapid review (5), Phase 1b modified Delphi study free-text comments (4), and Phase 2 qualitative descriptive study were covered by the modified Delphi study recommendations and behavioural analysis; therefore, they were not listed as reasons for inclusion to help keep the length/complexity of the table manageable.

[b] Features were classed as time-consuming to develop if they would require substantial programming time or involve developing a video, photograph, infographic, or Portable Document Format (PDF) document.

[c] If a feature was supported by more than one reason, the priority was based on the reason with the highest importance level.

[d] The barrier/facilitator sets were labelled with the codes reported in the behavioural analysis tables (Supplementary File 2).

Abbreviations: BSI, British Standards Institution; CGP, common guiding principle; NICE, National Institute for Health and Care Excellence; PAG, Project Advisory Group; PAS, Publicly Available Specification; PPI, Patient and Public Involvement; VGP, Virtual Knee School guiding principle; VKS, Virtual Knee School

Table 3: Virtual Knee School prototype design, build and testing process

Stage	Details	Activities[a]	Contributors[b]	Impact of feedback (key points)
Creation of a provisional VKS template and style guide	The lead researcher drafted six potential VKS design templates in Microsoft PowerPoint 2016, then used feedback on these to create a provisional VKS template and style guide.	Online Project Advisory Group meeting Online research team meeting One additional online meeting Telephone call Email correspondence	Two PAG PPI members PAG key collaborator member Four research team members	A turquoise/purple/blue colour scheme and a banner with three coloured triangles were chosen, as they were perceived to be the most aesthetically pleasing. A logo of a person demonstrating the knee straightening exercise was included without a motto, as the motto text would have been very small.
Creation of the VKS designs	The XX team used the provisional VKS template, style guide and content documents/files to create VKS designs in a PDF document, and then iteratively refined them based on the feedback obtained.	Two online scoping coproduction sessions with a member of the XX team Two additional online meetings Telephone call	Three PAG PPI members PAG independent chair Three research team members	Instructions on how to use the accessibility toolbar were added to the *'About the Virtual Knee School'* and *'Help'* pages due to concerns that users may miss the toolbar and/or not know how to use it. The *'slider'* (rotating content in the website banner) proposed by the XX team was removed due to concerns about its accessibility. *'Your most viewed pages'* hyperlinks were added to the footer to enable users to quickly navigate to their most frequently viewed pages.
Build of the VKS prototype	The XX team used the refined designs and content documents/files to build the VKS prototype on their Content Management System, and then iteratively refined it based on the feedback obtained.	Two online show and tell coproduction sessions with two members of the XX team	One PAG PPI member Four research team members	The instructions on how to use the accessibility toolbar were moved from the bottom to the top of the *'About the Virtual Knee School'* page to make them more obvious. Extra colour was added to the goal-setting page and icons were added to the goal-review page to make the pages more visually appealing. The goal review time limit was removed to allow users to review their goals at any time rather than needing to wait a week to maximise flexibility.

User acceptance testing	The lead researcher provided each formal tester with individualised instructions for testing the VKS prototype. The instructions were designed to ensure that all key functions were tested using a range of devices, operating systems, browsers, and accessibility software. Informal testers were invited to view the prototype and provide general comments. The lead researcher collated the feedback in a test log and addressed the feedback herself where possible and asked the XX team to address it if not.	Two online testing sessions One face-to-face testing session Online research team meeting Email correspondence	Formal testers: • Three PAG PPI members • Five research team members Informal testers: • Two PPI representatives • PAG key collaborator • Four health professionals/ researchers	Navigation instructions were added to the *'About the Virtual Knee School'* and *'Help'* pages for clarity. The word *'surgery'* was changed to *'operation'* where appropriate to improve clarity and readability, particularly for people with English as an additional language. *'Video'* was added to the titles of the videos to make it clear they were videos not static images. Instructions on how to play the videos/change the video settings were added as accordion content to all videos for clarity. Captions were turned on by default on all videos to improve accessibility. The login process and goal-setting feature error messages were updated for clarity. Back and next buttons were labelled with the names of the pages they go to for clarity. Buttons were added to the final page in each section to allow users to return directly to the homepage to improve the ease of navigation.

[a] The term *'coproduction'* refers to activities in which PAG PPI members played a direct role in making decisions (6).

[b] The lead researcher was involved in all the stages but is not listed in the contributors column.

Abbreviations: PAG, Project Advisory Group; PDF, Portable Document Format; PPI, Patient and Public Involvement; VKS, Virtual Knee School

Table 4: Criteria for implementing changes to the Virtual Knee School prototype

Code	Reason for change[a]	Importance level	Time consuming to implement[b]	Priority[c]
FSR	Important for the VKS functioning/navigation, safety, or compliance with relevant regulations/guidelines.	1	No	Must have
			Yes	Must have
VGP (VGP number)	Consistent with the VGPs developed in Phase 3.			
CGP (CGP number)	Consistent with the person-based approach CGPs (1).	2	No	Should have
EEQ (type)	Consistent with experience, evidence and/or the BSI PAS 277:2015 quality criteria (2). This includes changes supported by PAG member feedback, the NICE primary joint replacement guideline (3), the Phase 1b modified Delphi study recommendations (4), and/or the expertise of the research team.		Yes	Could have
BEH (target behaviour)	Likely to impact engagement with any of the following: • pre-op TKR care in a web-based format; • pre-op TKR education; • a pre-op TKR exercise programme; • healthy lifestyle changes. This includes, but is not limited to, changes that address barriers/facilitators identified in the Phase 3 behavioural analysis and changes that impact precursors to the desired behaviours e.g. acceptability, accessibility, persuasiveness etc.			
REP	Addresses a point repeated by more than one participant.			
EAS	Easy and uncontroversial as it does not require any substantial design changes e.g. amending a sentence for clarity.	3	No	Could have
			Yes	Would like
NTC	Does not contradict any of the criteria listed above. (Only listed in the table of changes if none of the criteria above applied).			
NTA (reason)	Not appropriate, for example due to contradicting one of the criteria listed above.	N/A	N/A	N/A

[a] Reasons for change criteria adapted from Bradbury et al. (7) and additional person-based approach resources (8, 9).

[b] Changes were classed as time-consuming to implement if they required substantial programming time; involved amending multiple pages; involved amending a static image or video; and/or involved developing a new page, video, photograph, infographic or portable document format (PDF) document.
[c] If a change was supported by more than one reason, the priority was based on the reason with the highest importance level. Changes considered *'Not appropriate'* were not prioritised.
Abbreviations: BSI, British Standards Institution; CGP, common guiding principle; N/A, not applicable; NICE, National Institute for Health and Care Excellence; PAG, Project Advisory Group; PAS, Publicly Available Specification; PPI, Patient and Public Involvement; pre-op, pre-operative; TKR, total knee replacement; VGP, Virtual Knee School guiding principle; VKS, Virtual Knee School

Table 5: Virtual Knee School guiding principles

VGP	Intervention design objective	Key intervention features
1	To provide a cost-effective, credible source of pre-operative TKR education and prehabilitation support that is widely/immediately accessible, easy to use and engaging for a wide range of users.	Being fully automated.
		Emphasising that the VKS is evidence-based, developed by a team of UK-based experts, and linked to the NHS.
		Ensuring all sections can be accessed rapidly during any session.
		Providing clear instructions on how to use the VKS, including a *'Help'* page at a minimum.
		Ensuring that the navigation and features are simple and quick to use.
		Providing PDF versions of key content/digital tools that users can download and print out, including a PDF exercise booklet and the documents listed under VGP-4 at a minimum.
2	To address users' potential concerns about pre-operative TKR education.	Emphasising that the VKS does not include any graphic details of TKR surgery.
		Providing brief information about TKR surgery only, without any graphic details.
		Ensuring that a range of appropriately moderated patient stories are provided, which are unlikely to be interpreted as *"horror stories",* and highlighting that everyone's preparations for/recovery from TKR surgery are different.
3	To account for users' varying pre-operative TKR education preferences and needs.	Providing pre-operative TKR education in accessible and engaging formats, ensuring key information is kept brief, but more detailed information is available for users who wish to access it.
		Providing information using simple language, avoiding medical terms where possible.
		Providing a glossary of medical terms.
		Providing key information using pictures and videos where appropriate, including videos related to understanding what to expect, pain management and rehabilitation (including using walking aids) at a minimum.
4	To address users' potential misconceptions about pre-operative TKR exercise and build their motivation to engage with the VKS exercise programme.	Providing reassurance that performing pre-operative exercises is safe for people with severe knee arthritis.
		Explaining the potential benefits of performing pre-operative exercises, including for post-operative recovery.
		Including patient stories modelling how other patients have benefitted from performing pre-operative TKR exercises.
		Providing features designed to motivate users to engage with the VKS exercise programme, including an online goal-setting feature that provides personalised feedback, a PDF goal-setting and recording sheet and a PDF exercise diary at a minimum.

5	To ensure that users with severe knee signs/symptoms and varying personal preferences and circumstances can safely engage with the VKS exercise programme.	Providing a flexible pre-operative TKR exercise programme that is tailored to the needs of users with severe knee signs/symptoms and does not require non-household equipment or facilities.
		Providing clear guidance about how to safely select, perform and progress exercises, including videos of relatable patient models demonstrating exercises at a minimum.
6	To ensure that users know how to make healthy lifestyle changes and build their motivation to do so.	Explaining the potential benefits of making healthy lifestyle changes, including for post-operative recovery.
		Including brief guidance on making healthy lifestyle changes, with signposting to credible sources of further guidance.

Abbreviations: NHS, National Health Service; PDF, Portable Document Format; TKR, total knee replacement; UK, United Kingdom; VGP, Virtual Knee School guiding principle; VKS, Virtual Knee School

Table 6: Summary of the main changes made to the Virtual Knee School prototype

VKS prototype section/aspect	Issues[a]	Main changes
Design and overall content	Not realising it was possible to select the accordions (expandable headings).	The accordions' background colour was changed to blue to distinguish them from other website features. Text was added to highlight that users can select the accordions.
	Feeling there was too much text.	Restructuring some of the text into accordions.
	Having difficulty locating and/or using the accessibility toolbar.	The accessibility toolbar instructions were updated for clarity. The accessibility toolbar header was amended to display *'Hide website accessibility tools'* when it was open and *'Show website accessibility tools'* when it was closed.
	Being concerned about whether there was enough time to watch the videos.	The duration of each educational video was added to its title. (Durations were also added to the exercise video titles but were misunderstood as referring to the durations of the exercises themselves, so were subsequently removed).
	Believing the patient stories were from real-life patients.	Text was added above the stories to explain that the stories were based on other patients' experiences.
Information architecture and navigation	Finding the tunnelling to the introductory section menu unhelpful/confusing.	The tunnelling was removed so that users went straight to the main homepage on their first login, and text was added to advise users to select the introductory section picture button if it was their first login.
	Feeling overwhelmed by the volume of content due to the education dropdown menu displaying the titles of all 24 education pages/subpages.	The education menu page was removed and the education subsections were promoted to full sections, limiting the number of page titles displayed at once to a maximum of eight.
	Not realising it was possible to select the small triangles to display lower-level pages when using the meganav on a mobile device in portrait orientation.	The size of the triangles in the meganav was increased.
	Feeling confused by the back and next buttons both going to the same page if the user accessed the last page in a section from the section menu.	The next buttons were removed from the final page in each section.
	Feeling extra hyperlinks would be useful for quickly checking other pages, and feeling confused about whether words in bold were hyperlinks.	Extra hyperlinks were added where appropriate.

Login section	Mistyping characters leading to the two passwords entered on the sign-up page not matching or the password entered on the login page being incorrect.	*'Show password'* options were added to the sign-up and login pages.
Main section	Feeling the main homepage did not make it clear that the website had three main sections.	The location and formatting of the button to the introductory section menu was amended so that the homepage included three picture buttons, corresponding with the three website sections. Text was added to explain how many sections the website has.
	Feeling it should be clearer that the website provides information related to the peri- and post-operative phases, rather than just the pre-operative phase.	The banner text on the main homepage and the text on the login page were updated to explain that the website is designed to help patients *'prepare for before, during and after'* TKR surgery.
	Feeling the three homepage picture buttons did not indicate where to find the information the user wanted.	The three education subsections were promoted to full sections so that the homepage included five picture buttons, corresponding with the five website sections, hence providing a greater level of detail about the information available. The title of the expectations section was changed from *'What to expect'* to *'About your operation*' for clarity.
	Feeling a link to the *'Contact us'* page should be included in the website footer for consistency with other websites.	A link to the *'Contact us'* page was added to the website footer.
	Considering using the VKS email address to ask questions about the user's own operation.	Text was added to clarify that users should contact their own care team for questions about their own operation and the VKS email address is only for questions about the VKS itself.
Introductory section	Feeling there was too much information on the introductory section menu.	The instructions on how to use the accessibility toolbar and website were moved into accordions.
	Feeling confused by the instructions on how to use the website.	Separate instructions were provided about how to use the website on computers and mobile devices. Labelled screenshots were added to the instructions.
	Finding the PDF of the Phase 1b modified Delphi study recommendations too detailed and *"very confusing".*	The document was deleted from the *'Virtual Knee School development and team'* page and a link to the Phase 1b journal publication was added to the *'Other helpful websites'* page instead.
	Feeling it would be helpful to amend the wording of certain answers on the *'Common questions'* page.	Minor text amendments were made to specific answers e.g. to highlight that exercising can help to relieve knee stiffness.

	Feeling it would be helpful to cover what to do if the user has bilateral knee problems on the *'Common questions'* page.	An accordion was added to explain that the VKS exercise programme is appropriate for people with bilateral knee problems.
Education section	Requesting further information about specific topics.	Hyperlinks to other pages of the prototype were added where appropriate e.g. a hyperlink to the *'Recovering from your operation'* menu was added to the *'After your hospital stay'* page. Minor text amendments were made where appropriate e.g. text was added to the *'Planning your return to work'* page to explain why users may want to keep their original fit note.
	Feeling the *'Goal setting'* page should provide more encouragement for users who do not meet their goals.	Text was added to provide more encouragement for users who do not meet their goals.
	Wanting post-operative goals to look forward to and *"something visual".*	An accordion with examples of post-operative goals to look forward to and a photograph of a beach were added.
Exercise section	Feeling confused about whether the exercise section was for the pre- or post-operative phase.	*'Pre-op'* was added to the exercise section title. The introductory text on the exercise section menu was amended for clarity.
	Highlighting queries or concerns about specific aspects of the exercise section text.	Minor text amendments were made where appropriate e.g. text was added to the exercise instructions to advise users to build up to exercising every day if they feel able to.
	Thinking the exercise category titles related to the videos above them rather than below them.	A horizontal line was added above and below each exercise category. The exercises were labelled to correspond with their category e.g. *'Category 1'* exercises were labelled as *'1a Seated Marching'*, *'1b Walking on the spot'* etc.
	Missing the *'Submit'* button on the goal-setting and review forms.	Text was added to the goal-setting and review forms to explain that users need to select the *'Submit'* button before proceeding to the next page.
	Entering numbers in the goal-setting form as words rather than numerals.	Text was added to the goal-setting form to advise users to enter numbers as numerals rather than words.
	Finding it challenging to set appropriate exercise goals due to unfamiliarity with the VKS exercise programme.	The exercise pages were reordered so that the *'Carry out an exercise session'* page was before the goal-setting pages. Text was added to the *'Set your exercise goals'* page to advise users to try carrying out a VKS exercise session before setting their goals.

[a] Supplementary File 3 provides an example quote for each issue.

Abbreviations: PDF, Portable Document Format; VKS, Virtual Knee School

References

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2. The British Standards Institution PAS 277:2015 Health and wellness apps – Quality criteria across the life cycle – Code of practice. BSI Standards Ltd; 2015.

3. National Institute for Health and Care Excellence (NICE). Joint replacement (primary): hip, knee and shoulder (NICE guideline [NG157]). 2020.

4. XX

5. XX.

6. O'Cathain A, Croot L, Duncan E, Rousseau N, Sworn K, Turner KM, et al. Guidance on how to develop complex interventions to improve health and healthcare. BMJ Open. 2019;9(8):e029954.

7. Bradbury K, Morton K, Band R, van Woezik A, Grist R, McManus RJ, et al. Using the Person-Based Approach to optimise a digital intervention for the management of hypertension. PLOS ONE. 2018;13(5):e0196868.

8. PBA: Person-Based Approach. Useful Resources. 2019. https://www.personbasedapproach.org/resources.html. Accessed 07 Sep 2019.

9. PBA: Person-Based Approach. Key Steps To Making And Using A Table Of Changes. 2022. https://www.personbasedapproach.org/table_of_changes.html. Accessed 06 May 2022.

Figure 1:

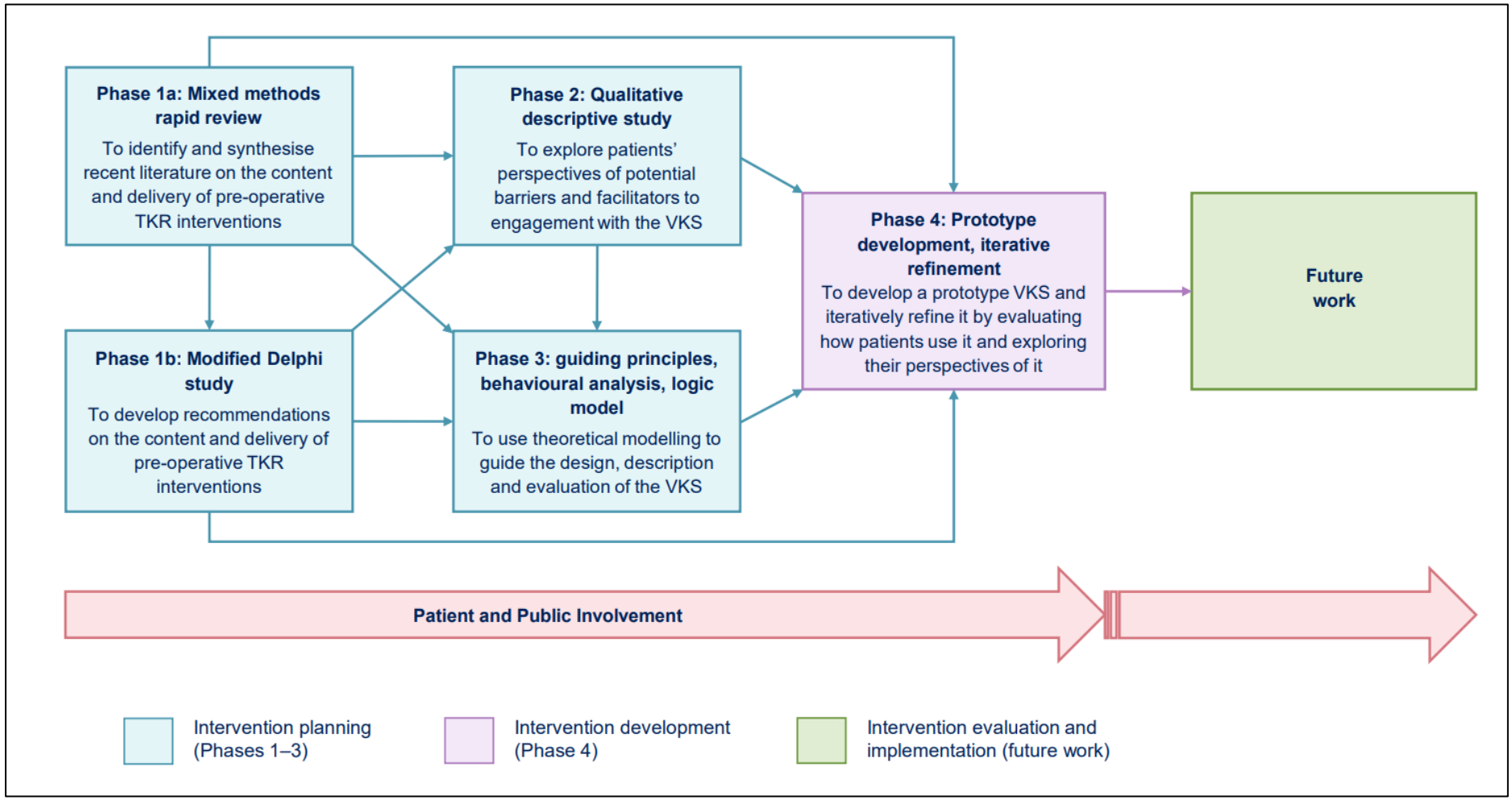

Phase 1a: Mixed methods rapid review
To identify and synthesise recent literature on the content and delivery of pre-operative TKR interventions
Phase 2: Qualitative descriptive study
To explore patients' perspectives of potential barriers and facilitators to engagement with the VKS
Phase 4: Prototype development, iterative refinement
To develop a prototype VKS and iteratively refine it by evaluating how patients use it and exploring their perspectives of it
Future work
Phase 1b: Modified Delphi study
To develop recommendations on the content and delivery of pre-operative TKR interventions
Phase 3: guiding principles, behavioural analysis, logic model
To use theoretical modelling to guide the design, description and evaluation of the VKS
Patient and Public Involvement
Intervention planning (Phases 1–3)
Intervention development (Phase 4)
Intervention evaluation and implementation (future work)

Figure 2:

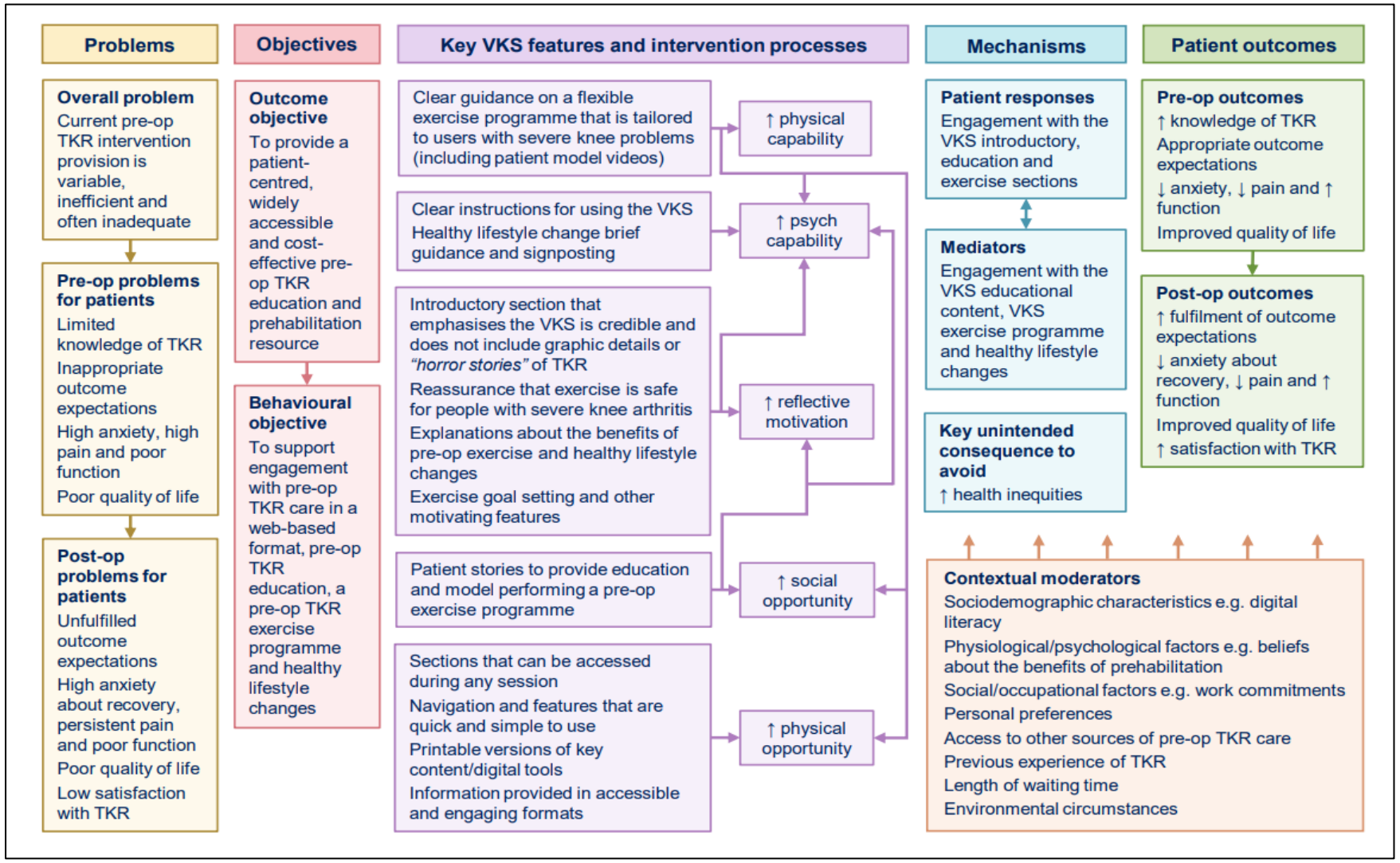
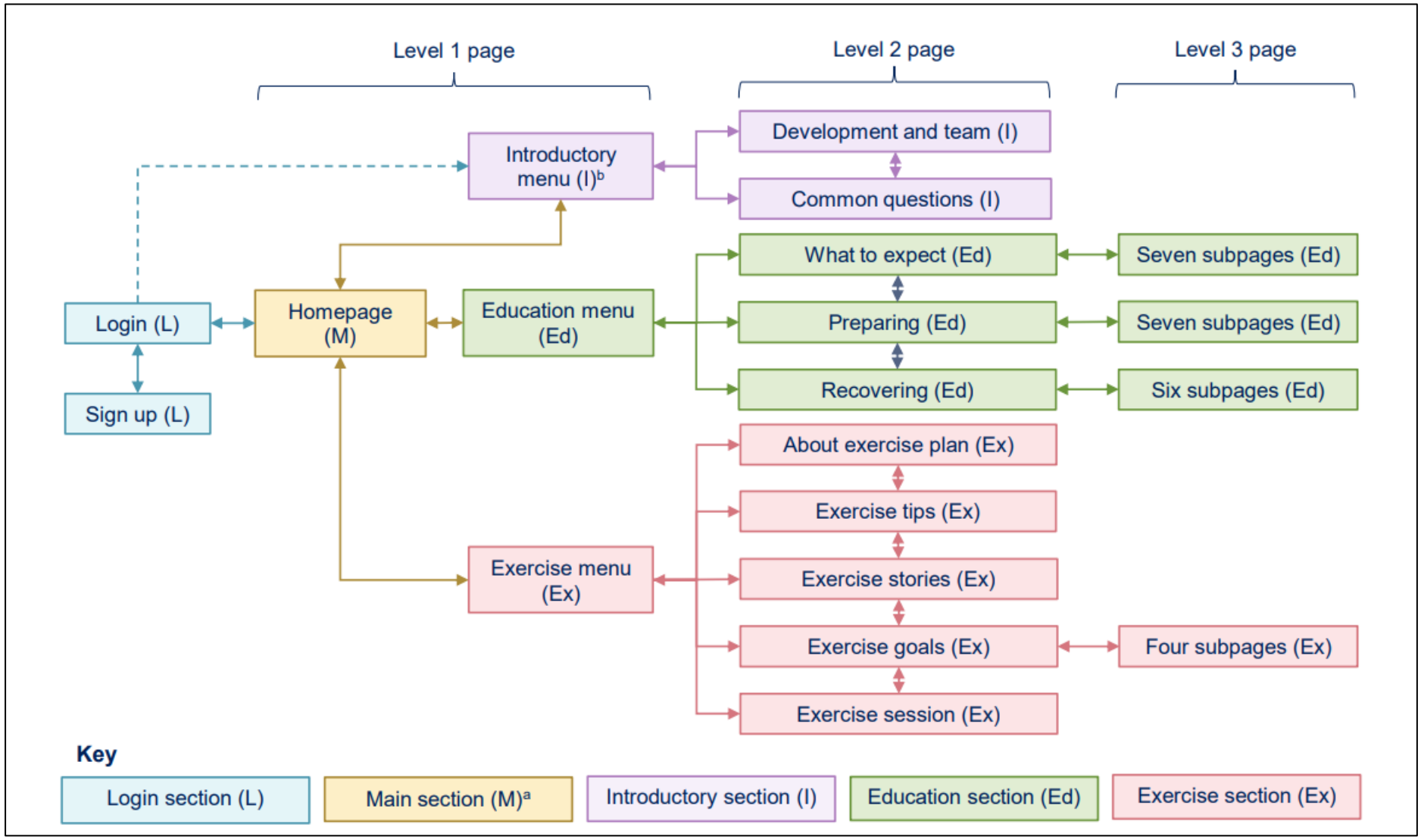

Problems
Overall problem
Current pre-op TKR intervention provision is variable, inefficient and often inadequate
Pre-op problems for patients
Limited knowledge of TKR
Inappropriate outcome expectations
High anxiety, high pain and poor function
Poor quality of life
Post-op problems for patients
Unfulfilled outcome expectations
High anxiety about recovery, persistent pain and poor function
Poor quality of life
Low satisfaction with TKR
Objectives
Outcome objective
To provide a patient-centred, widely accessible and cost-effective pre-op TKR education and prehabilitation resource
Behavioural objective
To support engagement with pre-op TKR care in a web-based format, pre-op TKR education, a pre-op TKR exercise programme and healthy lifestyle changes
Key VKS features and intervention processes
Clear guidance on a flexible exercise programme that is tailored to users with severe knee problems (including patient model videos)
Clear instructions for using the VKS
Healthy lifestyle change brief guidance and signposting
Introductory section that emphasises the VKS is credible and does not include graphic details or "horror stories" of TKR
Reassurance that exercise is safe for people with severe knee arthritis
Explanations about the benefits of pre-op exercise and healthy lifestyle changes
Exercise goal setting and other motivating features
Patient stories to provide education and model performing a pre-op exercise programme
Sections that can be accessed during any session
Navigation and features that are quick and simple to use
Printable versions of key content/digital tools
Information provided in accessible and engaging formats
↑ physical capability
↑ psych capability
↑ reflective motivation
↑ social opportunity
↑ physical opportunity
Mechanisms
Patient responses
Engagement with the VKS introductory, education and exercise sections
Mediators
Engagement with the VKS educational content, VKS exercise programme and healthy lifestyle changes
Key unintended consequence to avoid
↑ health inequities
Patient outcomes
Pre-op outcomes
↑ knowledge of TKR
Appropriate outcome expectations
↓ anxiety, ↓ pain and ↑ function
Improved quality of life
Post-op outcomes
↑ fulfilment of outcome expectations
↓ anxiety about recovery, ↓ pain and ↑ function
Improved quality of life
↑ satisfaction with TKR
Contextual moderators
Sociodemographic characteristics e.g. digital literacy
Physiological/psychological factors e.g. beliefs about the benefits of prehabilitation
Social/occupational factors e.g. work commitments
Personal preferences
Access to other sources of pre-op TKR care
Previous experience of TKR
Length of waiting time
Environmental circumstances

Figure 3:


Level 1 page
Level 2 page
Level 3 page
Introductory menu (I)b
Development and team (I)
Common questions (I)
Login (L)
Homepage (M)
Education menu (Ed)
What to expect (Ed)
Seven subpages (Ed)
Preparing (Ed)
Seven subpages (Ed)
Recovering (Ed)
Six subpages (Ed)
Sign up (L)
About exercise plan (Ex)
Exercise tips (Ex)
Exercise menu (Ex)
Exercise stories (Ex)
Exercise goals (Ex)
Four subpages (Ex)
Exercise session (Ex)
Key
Login section (L)
Main section (M)a
Introductory section (I)
Education section (Ed)
Exercise section (Ex)

Supplementary File 1: Phase 4 methods supporting information

Table S1: Virtual Knee School education section intervention planning table excerpt

Page(s)	VKS feature	Importance level[a]			Time-consuming to develop	Priority	Include in prototype
		1	2	3			
Managing concerns during your recovery	Text covering how to lower the risks of having issues after TKR surgery, including wound care	–	NICE; VIR (1.14)	–	No	Should have	Yes
	Traffic light system checklist that: • includes complications of TKR surgery and common issues that do not need to cause alarm • explains how to organise help if complications occur	–	VIR (1.14, 1.15)	IR (1.33); BF (Ed3)	No	Should have	Yes
Getting up and about	Brief videos of patient models demonstrating how to use: • a walking stick • one and two crutches • a walking frame	VGP (3)	PPI	IR (1.8, 1.34); BF (W3, Ed2, Ed3)	Yes	Must have	Yes
	Text covering post-operative mobility, including: • the role of mobilising in rehabilitation following TKR surgery • the role of mobilising in lowering the risks of TKR surgery • key points about mobilising safely	–	VIR (1.14, 1.20)	IR (1.34)	No	Should have	Yes
	Accordion content covering: • returning to a normal walking pattern • how to stand up, sit down and perform bed transfers	–	–	IR (1.8, 1.34); BF (W3, Ed3)	No	Could have	Yes

	PDF booklets covering how to use walking aids	–	PPI	IR (1.8, 1.34, 2.5.3, 2.6)	Yes	Could have	No
	Photographs of a patient model getting up with one foot in front of the other and getting up with their feet in line	–	–	BF (Ed2)	Yes	Would like	No
	Photograph of a patient model getting on and off a bed	–	–	BF (Ed2)	Yes	Would like	No
	Brief video of a patient model getting up with one foot in front of the other and getting up with their feet in line	–	–	BF (W3, Ed2, Ed3)	Yes	Would like	No
	Brief video of a patient model getting on and off a bed	–	–	BF (W3, Ed2, Ed3)	Yes	Would like	No

[a] Table 2 in the main paper provides the meaning of the codes.

Abbreviations: PDF, Portable Document Format; TKR, total knee replacement; VKS, Virtual Knee School

Virtual Knee School exercise programme design overview

The Virtual Knee School (VKS) exercise programme was designed using a multi-step process.

1. A list of target exercise types to include in the VKS exercise programme was identified from the final set of recommendations developed in the Phase 1 modified Delphi study (1). A table was created to document the target exercise types, exercises that could be classified as each exercise type, and considerations for deciding which exercise types/exercises to include in the VKS prototype (Table S2).
2. The findings from Table S2 and research team discussions were used to develop proposed exercise categories for the VKS exercise programme and a prioritised list of candidate exercises for each category (Table S3).
3. The findings from Table S3 and research team discussions were used to develop a table summarising the proposed exercise categories and exercises to be included in the VKS. This was refined based on discussions with two Project Advisory Group (PAG) Patient and Public Involvement (PPI) members to create the finalised list of VKS exercise categories and exercises (Table S4).
4. A proposed delivery format for the VKS exercise programme was developed based on the final set of recommendations developed in the Delphi study (1) and research team discussions (Table S5). The delivery approaches were discussed with two PAG PPI members, who felt no changes were needed.

Table S2: Target exercise types

Target exercise type (Phase 1b modified Delphi study item number (1))[a]	Exercises classified as the exercise type in randomised studies of pre-operative interventions included in the Phase 1a rapid review (2)[bc]	Exercises identified from additional sources [source][b]	Considerations for including the exercise type/potential exercises in the VKS prototype
Leg strengthening exercises (Item 3.1)	• Squats with elastic resistance (3-5) • Dynamic stepping exercise (6) • Hip extension (with a strength training machine or with elastic resistance) (4, 5, 7) • Hip flexion with elastic resistance (4, 5) • Hip abduction (with a strength training machine or with elastic resistance, on an even or an uneven surface) (4, 5, 7-11) • Hip adduction (with a strength training machine or with elastic resistance, on an even or an uneven surface) (4, 7, 10, 11) • Seated leg press (with a strength training machine) (7-9) • Knee extension (with elastic resistance, with a strength training machine or with no external resistance, in sitting) (4-12) • Isometric quadriceps contraction in full extension using a rolled towel under the knee in supine (6) • Hamstring flexion/leg curl (with elastic resistance, with a strength training machine or with no external resistance, in prone/side lying or in sitting) (3-11) • Unspecified quadriceps strengthening (13)	• Dynamic joint movements and dynamic body weight movements, including step-ups and calf raises [RR (8, 9)] • *"Leg lifts with rolled towel under knee"* [DC] • *"Terminal knee extensions"* [DC] • *"Straight leg raises"* [PPI]	• Exercises that require elastic resistance or a strength training machine are inconsistent with VGP-5 due to requiring specific equipment. However, many of the exercises listed as being performed with elastic resistance or a strength training machine can be performed in alternative ways that do not require equipment. • *'Dynamic joint movements and dynamic body movements'* can include multiple different exercises. • *'Dynamic stepping exercise'* / *'Step-ups'* can also be classified as a *'Functional movement exercise'*, *'Cardiovascular exercise'* and *'Training on steps'*.

	• Ankle dorsiflexion with elastic resistance (3-5) • Ankle plantar flexion with elastic resistance (3-5)		
Leg flexibility exercises (Item 3.3)	• Gluteal stretch (14) • Hip extensor stretch (3) • Hip flexor stretch (3) • Hip adductor stretch (14) • Knee extensor/quadriceps stretch (in sitting) (3, 6, 7, 14) • Knee flexor/hamstring stretch (in sitting) (3, 6, 7, 14) • Ankle flexors/gastrocnemius stretch (7, 14)	• Gluteal stretch [RR (4, 5)] • Hip stretch [RR (4, 5)] • Hip abductors stretch [RR (8, 9)] • Knee extensors stretch [RR (8, 9)] • Knee flexors/hamstring stretch [RR (4, 5, 8, 9)] • Ankle plantar flexors/calf stretch [RR (4, 5, 8, 9)] • Unspecified lower limb mobility exercises and stretches (one exercise is shown but was used for patients with hip osteoarthritis only) [RR (10, 11)]	None of note.
Balance exercises (Item 3.6)	• Double leg stance on an unstable device (8, 9) • Single leg stance (on an unstable device, hard floor or balance mat, with or without support, with eyes open or closed) (8, 9, 14) • Slide step forward/backward on a hard floor or balance mat, with or without support, with eyes open or closed (14) • Step forward/backward on a hard floor or balance mat, with or without support, with eyes open or closed (14) • Squats on a hard floor or balance mat, with or without support, with eyes open or closed (14)	• *"Balancing on Bosu"* [DC] • *"Heel to toe walking"* [RR (14), PPI]	• Exercises that require a balance device/mat are inconsistent with VGP-5 due to requiring specific equipment. • *'Slide step forward/backward'* and *'Step forward/backward'* can also be classified as *'Leg strengthening exercises'* and *'Functional technique exercises'*. • *'Squats'* can also be classified as a *'Leg strengthening exercise'*.
Functional movement	• Forward step ups, with or without hand support or bar bells (10, 11)	• Transfer training (bed, vehicle and toilet transfers) [DC (two panellists)]	• Transfer training will be addressed in the education section of the VKS.

exercises (Item 3.7)	• Chair stands, with or without hand support, with feet parallel or with one foot forward (10, 11)		• Forward step-ups can also be classified as a *'Leg strengthening exercise'*, *'Cardiovascular exercise'* and *'Training on steps'*. • Chair stands can also be classified as a *'Leg strengthening exercise'* and *'Cardiovascular exercise'*.
Functional technique exercises (Item 3.8)	• Slide-exercise forward-backward on an even or uneven surface, with flexion/extension of the weight-bearing knee (10, 11) • Slide-exercise sideways on an even or uneven surface, with flexion/extension of the weight-bearing knee (10, 11) • Forward lunge, with hand support if required (10, 11) • Sideways lunge, with hand support if required (10, 11)	• Walking forward and backwards in front of a mirror [RR (10, 11)]	• Walking forward and backwards in front of a mirror is inconsistent with VGP-5 due to requiring specific equipment. • Slide-exercise forward-backward and slide-exercise sideways can also be classified as *'Leg strengthening exercises'* and *'Balance exercises'*. • Forward lunge and sideways lunge can also be classified as *'Leg strengthening exercises'* and *'Balance exercises'*.
Cardiovascular exercises (Item 3.11)	None – cardiovascular exercises were added to Round 1 based on project team discussions during the pilot testing process.	• Unweighted leg joint movements [RR (3)] • Walking (fast-paced) [RR (4, 5, 14)] • Ergometer cycling (hand or leg) [RR (7-11)]	• *'Unweighted leg joint movements'* can include multiple different exercises. • *'Ergometer cycling'* is inconsistent with VGP-5 due to requiring specific equipment. • *'Walking'* and *'Ergometer cycling (leg)'* can also be

			classified as *'Leg strengthening exercises'*.
Core control exercises (Item 3.12)	• Pelvic lifts with gym ball (10, 11) • Sit-ups with gym ball (10, 11)	None	• Exercises that require a gym ball are inconsistent with VGP-5 due to requiring specific equipment. However, both core control exercises listed can be performed without a gym ball.
Walking practice with walking aids (Item 3.13)	None – this exercise type was included in the Round 1 survey based on a study exploring patients' and health professionals' views of pre-operative interventions (15)	None	• This exercise type is inconsistent with VGP-5 due to requiring specific equipment. However, *'Walking'* alone is consistent with VKS guiding principles. • Guidance on obtaining and using walking aids will be included in the VKS education section.
Training on steps (Item 3.14)	• Forwards step-ups (3-5) • Lateral step-ups (3-5)	None	• *'Forward step-ups'* and *'Lateral step-ups'* can also be classified as *'Leg strengthening exercises'*, *'Functional movement exercises'* and *'Cardiovascular exercises'*
Practicing post-operative exercises (Item 3.15)	None – this exercise type was added to Round 2 based on content analysis of the Round 1 free-text responses.	• Knee flexion/extension in sitting with a sliding device (e.g. plastic bag or skateboard) under the foot [PPI, DC]	• All the exercise listed are appropriate to perform post-operatively, although some are not appropriate in the early post-operative phase.

			• *'Knee flexion/extension in sitting with a sliding device'* can also be classified as a *'Leg flexibility exercise'.*

[a] All the exercise types included in the final set of recommendations developed in the Phase 1b modified Delphi study were considered target exercise types for inclusion in the VKS.
[b] Exercises were only identified from studies that were identified prior to the rapid review search updates and reported a statistically significant difference in favour of the intervention group for at least one outcome at one or more follow-up time points.
[c] The exercise classifications were based on the primary study authors' descriptions. Details in brackets were specified in at least one, but not all, of the studies listed.
Abbreviations: DC, free-text comment provided by a panellist in the Phase 1b modified Delphi study; PPI, free-text comment provided by a Patient and Public Involvement representative during pilot testing of Round 1 of the Phase 1b modified Delphi study; RR, exercise identified from the warm-up or cool-down of a randomised study of a pre-operative intervention(s) included in the Phase 1a rapid review; VGP-5, Virtual Knee School guiding principle 5; VKS, Virtual Knee School

Table S3: Proposed Virtual Knee School exercise categories and candidate exercises

Proposed exercise category[a]	Prioritised candidate exercises[ab]	Explanation
Aerobic fitness	1. Walking or marching on the spot *(standing)* 2. Step-ups (forward step-ups) *(standing)* 3. Seated marching *(sitting)* 4. Sideways step-ups (lateral step-ups) *(standing)*	• This exercise category focuses primarily on *'Cardiovascular exercises'* and *'Training on steps'*. • *'Marching on the spot'* was added as an alternative to walking to account for users with limited space. • *'Seated marching'* was selected as an appropriate *'Unweighted leg joint movements'* exercise. • It was decided to name this category *'Aerobic fitness'* because the included exercises will raise users' heart rates.
Knee strength and endurance	1. Chair stands *(sitting/standing)* 2. Knee straightening (knee extensions) *(sitting)* 3. Straight leg raise *(crook lying)* 4. Mini squats (squats) *(standing)* 5. Leg lifts with a rolled towel under the knee *(long sitting)*	• This exercise category focuses primarily on *'Leg strengthening exercises'* and *'Functional movement exercises'*. • Improving knee extensor muscle strength is a key target of TKR prehabilitation (16). Therefore, it was agreed it was important to separate *'Leg strengthening exercises'* into two separate sections, one focusing solely on knee extensor exercises and one focusing on hip and ankle exercises. Correspondingly, it was decided not to include *'Hamstring flexion/leg curl'* in this category to help ensure that users perform at least one knee extensor strengthening exercise. • Given the exercises listed may improve both muscle strength and endurance, it was decided to name this category *'Knee strength and endurance'*.
Hip and ankle strength and endurance	1. Heel raises (calf raises) *(standing)* 2. Sideways leg lifts (hip abduction) *(standing/side lying)* 3. Backwards leg lifts (hip extension) *(standing/prone)* 4. Knee lifts (hip flexion) *(standing)* 5. Toe lifts (ankle dorsiflexion) *(standing)* 6. Towel squeezes (hip adduction) *(sitting)*	• This exercise category focuses on *'Leg strengthening exercises'*. • Exercises listed as being performed with elastic resistance or a strength training machine in the rapid review studies have been adapted so that they can be performed without requiring specific equipment.

		• As above, it was decided to name this category '*Hip and ankle strength and endurance'* because the exercises listed aim to improve muscle strength and endurance.
Balance and stability	1. Standing on one leg (single leg stance) *(standing)* 2. Hip lifts (pelvic lifts) *(crook lying)* 3. Step forwards/backwards (forward lunge) *(standing)* 4. Heel to toe walking *(standing)* 5. Slide-exercise sideways *(standing)* 6. Slide-exercise forwards/backwards (slide step forward/backward) *(standing)* 7. Step sideways (sideways lunge) *(standing)* 8. Sit-ups *(crook lying)*	• This exercise group focuses primarily on *'Balance exercises'*, *'Functional technique exercises'* and *'Core stability exercises'.* • *'Step forwards/backwards'* is considered to include *'Forward lunge'* as the size of the step forwards can be varied. • *'Slide step forwards/backwards' and 'Slide-exercise forwards/backwards'* are listed as different exercise types in the target exercise types table but are considered the same exercise.
Leg stretching and flexibility	1. Thigh stretch (knee extensor stretch) *(standing/side lying)* 2. Hamstring stretch *(standing/sitting)* 3. Knee bending/straightening (knee flexions/extensions in sitting with a sliding device) *(sitting)* 4. Calf stretch *(standing)* 5. Buttock stretch (gluteal stretch) *(long sitting)* 6. Knee to chest stretch (hip extensor stretch) *(crook lying)* 7. Inner thigh stretch (hip adductor stretch) *(standing/sitting)* 8. Hip stretch *(standing)*	• This exercise category focuses on *'Leg flexibility exercises'* and *'Practicing post-operative exercises'.*

[a] The exercise categories/candidate exercises covered all the target exercise types except for *'Walking practice with walking aids'* because requiring specific equipment is inconsistent with Virtual Knee School (VKS) guiding principle 5 and the VKS education section provides guidance on using walking aids.
[b] Bracketed plain text indicates the original description of the exercise, which was amended for clarity. Bracketed text in italics indicates the exercise position(s). It was provisionally decided to include the top three candidate exercises from each category in the VKS exercise programme; therefore, the prioritisation aimed to ensure that the top three exercises in each category varied in difficulty and included at least one non-weight bearing exercise to address VKS guiding principle 5, and that the top three exercises from all five categories combined covered all the target exercise types except *for 'Walking practice with walking aids'*.
Abbreviations: TKR, total knee replacement

Table S4: Finalised Virtual Knee School exercise categories and exercises

Exercise category	Exercises
1. Aerobic fitness	Seated marching Walking on the spot Step-ups
2. Knee strength and endurance	Straight leg raise Knee straightening Sit to stand
3. Hip and ankle strength and endurance	Sideways leg lifts Backwards leg lifts Heel raises
4. Balance and stability	Hip lifts Standing on one leg Step forwards and backwards
5. Leg flexibility	Thigh stretch Hamstring stretch Calf stretch

Table S5: Virtual Knee School exercise programme delivery approaches

Delivery category	Phase 1b modified Delphi study final recommendation (item number(s) (1))	Addressed in the VKS	Explanation
Delivery mode	Be delivered using a combination of more than one format, including supervised exercise sessions, unsupervised exercise sessions and a booklet or other written format (4.1.2; 4.1.3; 4.1.5; 4.2)	Partly	The exercise programme was provided directly on the VKS prototype through text/videos with captions and as a PDF booklet that users could download.
	Provide an opportunity for peer support (4.11)	No	An online discussion forum would require moderation. This would be inconsistent with VGP-1.
	Include goal setting (4.12)	Yes	The VKS prototype included a goal-setting feature (details below).
Intensity	Include exercises which are low to moderate intensity (4.4.2)	Yes	The exercise instructions recommended starting at a low level and slowly building up to a medium level.
	Be progressive (4.6)	Yes	The exercise instructions encouraged users to progress by: • increasing the number of exercise sessions they perform per week; • increasing the intensity of the exercises; • increasing the number of exercises they perform per session.

Schedule	Involve exercise sessions which last a minimum of fifteen minutes each (4.7)	Yes	The exercise instructions recommended selecting at least one exercise from each category (five exercises in total) and performing three sets of 30 seconds of each exercise, with a 30-second rest after each set.
	Involve a minimum of two exercise sessions per week (4.8)	Yes	The exercise instructions encouraged users to perform at least two exercise sessions per week.
	Ideally be performed for a minimum of six weeks (4.9)	Partly	The exercise instructions encouraged users to start the programme as soon as possible. A specific timeframe was not provided because patients remain on the TKR waiting list for varying lengths of time.
Tailoring	Be tailored according to each patient's individual needs and ability (4.5; 4.10)	Yes	The content and delivery of the exercise programme were self-tailored because users could choose from a range of exercises and adapt the intensity and schedule to meet their individual needs and ability.

Abbreviations: PDF, Portable Document Format; TKR, total knee replacement; VGP-1, Virtual Knee School guiding principle 1; VKS, Virtual Knee School

Think-aloud interview recruitment approaches

As detailed in the main paper, participants were recruited via a National Health Service Teaching Hospital and word of mouth. The following recruitment approaches were also employed with the aim of facilitating the recruitment of patients who were male and/or from a Black, Asian, or other minority ethnic group.

1. A PAG PPI member shared a WhatsApp message with contacts in her communities.
2. Recruitment adverts were posted on Twitter and Facebook.
3. Two local community networks that work with people from underserved groups were approached.

The WhatsApp message and social media adverts included details of specific eligibility criteria, for example to highlight that people from Black, Asian, or other minority ethnic groups were particularly welcome.

No participants were recruited in response to the WhatsApp message or social media adverts, and neither of the community networks approached were willing to share the recruitment adverts.

Think-aloud interview topic guide

The think-aloud interview topic guide provided below was developed based on the Phase 4 objectives and an example think-aloud topic guide for person-based approach intervention development studies (17). Neither of the two PAG PPI members who were invited to review the topic guide suggested any changes. The lead researcher pilot tested the topic guide with another member of the research team prior to the first interview. No modifications were made to the topic guide during the study.

Development of a Virtual Knee School, Phase 4, think-aloud interview topic guide

IRAS 262809; version 3.0, dated 04 Aug 2021

The following topic guide may be modified during the data collection phase so that themes identified in earlier interviews can be explored in later interviews. Each participant will complete two interviews. This topic guide will be used for both interviews. Consent will have been obtained online prior to the participant's first interview.

Interview Introduction

The interviewer should complete all the following actions prior to commencing the interview

1. Review the information provided in the Participant Information Sheet, including:
    - Aim of the study
    - Participant can withdraw at any time

- Interview will be recorded with an encrypted mobile phone, laptop and/or secure video conferencing tool
- Confidentiality

2. Explain the process for the interview, including:
    - Participant should say what they are thinking out loud as they work through the Virtual Knee School
    - Interviewer may ask prompt questions
    - Interview is not a test and there are no right or wrong answers
    - Interviewer cannot answer questions during the interview, but can discuss them at the end
    - Interviewer may ask the participant to access specific information/sections/pages of the Virtual Knee School
    - Once the participant has finished working through the Virtual Knee School, the interviewer will ask questions about the participant's overall views of the Virtual Knee School
3. Reiterate the Virtual Knee School is still in development and is not fully ready to be used
4. Offer the participant an opportunity to ask questions

Think-aloud Prompts

The interviewer may ask the participant any of the following prompt questions as the participant works through the Virtual Knee School. Each prompt may be used multiple times, if appropriate. The prompts may be adapted/expanded for clarity.

1. Can you tell me what you think about the <<insert website content>> on this page?
2. Can you tell me how you feel about using <<insert digital feature/activity/tool>>?
3. Can you tell me what you like about <<insert website content/digital feature/activity/tool>>?
4. Can you tell me what you DON'T like about <<insert website content/digital feature/activity/tool>>?
5. Can you tell me why you selected that?
6. Can you tell me about your overall views of this page?
7. Can you tell me what you are thinking at the moment?

8. Can you explain that a bit more?

Post-Think-aloud Prompts

1. What are your overall views of the Virtual Knee School?
2. Can you tell me about anything you particularly liked about the Virtual Knee School?
3. Can you tell me about anything you particularly DIDN'T like about the Virtual Knee School?
4. How do you think the Virtual Knee School could be improved?
5. Is there anything else you would like to add?

Interview closure

The interviewer should complete all the following actions after the interview is completed

1. Thank the participant for taking part in the interview
2. If the interview was the participant's first interview, confirm the plan for their second interview
3. Offer the participant an opportunity to ask questions
4. Complete the travel expenses form if the interview took place at [recruitment site]

Table S6: Table of changes main section excerpt

Page/ aspect	Positive comment [participant pseudonym]	Negative comment [participant pseudonym]	Suggested change	Reason for change[a]	Time-consuming to implement	Priority MoSCoW	Change agreed	Date change implemented[b]
Homepage		Does not feel it is clear from the homepage that the website has three key sections. [Glen]	Add text to the homepage to explain that the website has three key sections.	VGP (1) BEH (web-based) EAS	No	Must have	Agreed 28/10/2021	28/10/2021
			Change the *'About the Virtual Knee School'* text button to a picture button next to the buttons to the other key sections (so that there are three picture buttons corresponding with the three key sections).	VGP (1) BEH (web-based)	No	Must have	Agreed 28/10/2021	28/10/2021
	Likes colour, layout and "*less writing"* (compared to the *'About the Virtual Knee School'* page). Feels it is *"very clear but not*							

	overwhelming". [Ella] Feels the page layout is clear. [Arthur] Feels the page layout is *"easy to use, clear, and not confusing."* [Haaniya] Feels the page layout *"works, and it's nice, 'cause it's very visual, so it makes it more appealing doesn't it? It's not just all text."* [Naomi] Feels the homepage layout is *"helpful".* [Zuri]							

[a] The meanings of the codes are provided in Table 4 in the main text.

[b] An additional column called *'Notes'* was included in each Excel sheet but is not shown due to space limitations. The *'Notes'* column was used to document any key points related to the potential change, such as comments from the research team discussions and the time requirements for changes that would have to be made by the XX team rather than the research team.

Abbreviations: MoSCoW, *'Must have, Should have, Could have, Would like'* model (18, 19)

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Supplementary File 2: Phase 3 findings supporting information

Groups of considerations used to develop the Virtual Knee School guiding principles

Six groups of considerations related to the intended Virtual Knee School (VKS) users' characteristics, context and needs were identified from the sources in Table S7. Each group of considerations was used to develop a guiding principle as detailed in the main paper.

Table S7: Key sources used during the theoretical modelling

Code	Source
PPI-C	Patient and Public Involvement consultations held during the project planning.
RR (study citation)	Findings from the Phase 1a rapid review studies (1).
DR (item number)	Final set of recommendations developed in the Phase 1b modified Delphi study (2).
DC	Free-text comments provided by patients and/or professionals in the Phase 1b modified Delphi study (2).
FG	Focus group findings from the Phase 2 qualitative descriptive study.

1. Pre-operative total knee replacement (TKR) intervention provision and digital delivery

There are substantial discrepancies in current United Kingdom (UK) pre-operative total knee replacement (TKR) intervention provision [PPI-C; FG]. Some patients do not receive sufficient pre-operative TKR education and prehabilitation support or do not receive it long enough before their surgery [PPI-C; DC; FG]. These inadequacies may encourage patients to engage with web-based pre-operative TKR care [FG]. However, some patients may not be able to access websites [PPI-C; DC]. Even patients who can access websites may be reluctant to use them [FG]. Some patients have concerns about the reliability of websites and/or the detail/duration of website interactions [PPI-C; FG]. Furthermore, patients' experience of using digital tools and preferences for digital features vary widely [FG].

2. Pre-operative TKR education concerns

Although some patients want to find out what happens during TKR surgery, others may be concerned about receiving information about the TKR surgical procedure, particularly due to the risk of seeing graphic details of surgery [RR (3); DC; FG]. In addition, patients may have concerns about hearing *"horror stories"* of TKR [FG]. Hearing such stories may impair patients' ability to learn [RR (4)]. Patients may also be concerned about making comparisons with other patients [FG]. On the other hand, for some patients, a desire to find out about other patients' experiences of TKR may be a facilitator to engagement with pre-operative TKR education [RR (5); FG].

3. Pre-operative TKR education preferences and needs

Patients' preferences for pre-operative TKR education vary widely, with some patients wanting to receive as much pre-operative information as possible, whilst others do not want to receive detailed information [RR (3); FG]. Patients' learning styles also differ [RR (6)]. In addition, patients may have low literacy and/or face language barriers [RR (6); DC; FG]. Correspondingly, some patients need simple information, but others find large volumes of simple information frustrating [FG]. Some patients value educational videos, especially of practical tasks such as how to use walking aids [FG]. Key topics that patients want information on include understanding what to expect, pain management and rehabilitation [PPI-C; RR (3, 5, 7-9); DR (1.12; 1.14–1.20); DC; FG].

4. Pre-operative TKR exercise misconceptions and motivating factors

Some patients may be concerned that exercising will cause further knee damage [PPI-C; FG]. Patients may also believe that pre-operative exercises are not important/beneficial [RR (10); DC]. This belief may be reinforced by health professionals [DC; FG]. Conversely, patients may be particularly motivated to perform pre-operative TKR exercises by the belief that doing so will improve their post-operative recovery and a sense of personal

responsibility for their own recovery [RR (5); DC; FG]. Patients may also be motivated to engage with pre-operative exercises by setting goals/receiving tailored feedback and monitoring their exercise completion [FG]. Correspondingly, goal setting was identified as an important element of pre-operative TKR exercise programmes during the Phase 1b modified Delphi study [DR (4.12)].

5. Pre-operative TKR exercise preferences and needs

Patients listed for TKR surgery typically have severe knee signs/symptoms, which can prevent them from exercising [DC; FG]. Patients' engagement with pre-operative exercises may also be limited by a lack of guidance, being busy with other commitments/distractions and additional personal preferences/circumstances such as a dislike of certain exercise types, having other health issues and not being able to access specific equipment/facilities [PPI-C; RR (10); FG]. Patients' preferences for exercise videos versus exercise animations vary [FG]. Some patients particularly value exercise videos with real-life models, but videos may have a negative impact if patients cannot relate to the models [FG].

6. Pre-operative healthy lifestyle change motivating factors, needs and preferences

Patients may be motivated to make pre-operative healthy lifestyle changes by the belief that doing so will improve their post-operative recovery, a sense of personal responsibility for their own recovery and strategies such as self-monitoring and reflection [RR (5, 11, 12); FG]. As for pre-operative exercise, patients' engagement with healthy lifestyle changes may be limited by a lack of guidance [FG]. However, credible sources of healthy lifestyle guidance that account for individuals' differing needs/preferences are already available [FG].

Behavioural analysis tables overview

Behavioural analysis tables were created for each behaviour targeted by the VKS (tables S8–S11). Sets of barriers and facilitators to the target behaviours and potential VKS features

that could address the barriers and facilitators were identified from the sources listed in Table S7. Extra features were added based on project team discussions. All the features were mapped to components of the Capability, Opportunity, Motivation, Behaviour (COM-B) model of behaviour (13), intervention functions from the Behaviour Change Wheel (BCW) (13), and behaviour change techniques from the Behaviour Change Technique Taxonomy v1 (BCTTv1) (14).

Table S8: Behavioural analysis table for engagement with pre-operative TKR care in a web-based format

Set of barriers/*facilitators* to the target behaviour [barrier/facilitator/VKS feature source(s)[a]]	Potential VKS feature(s) that could address the barriers/facilitators	Target component(s) (BCW)	Intervention function(s) (BCW)	Behaviour change technique(s) (BCTTv1)
W1. Limited experience of using digital tools/low digital literacy [RR (15); FG]	Simple navigation, including menu pages with links to other sections/pages.	Physical opportunity	Environmental restructuring	12.1 Restructuring the physical environment
	Introductory section that provides clear instructions about how to use the VKS and emphasises that it is easy to use, even for people who have limited experience of using digital tools. *'Common questions'* and *'Help'* pages available to assist users with using the VKS.	Psychological capability Reflective motivation	Education Persuasion	4.1 Instruction on how to perform the behaviour 15.1 Verbal persuasion about capability
W2. Reluctance to use digital technologies Concerns about the reliability of websites Concerns about receiving conflicting information [PPI-C, RR (7); FG]	Introductory section that: • highlights the potential benefits of using the VKS, including that it supports users to prepare for TKR surgery, understand what to expect and perform a pre-operative exercise programme, which could help improve users' post-operative recovery; • explains that the VKS adds to the guidance patients get from their own care team and patients should always follow guidance from their own care teams; • highlights that the VKS is NIHR-funded (and so linked to the NHS) and has been developed by experts based on evidence and feedback from patients;	Psychological capability Reflective motivation	Education Persuasion	5.1 Information about health consequences 5.6 Information about emotional consequences 9.1 Credible source

	• includes names, biographies and/or photographs of team members; • acknowledges that some people are reluctant to use digital technologies and explains that the VKS provides documents that users can download and print out where appropriate.			
	Documents that users can download and print out.	Physical opportunity	Environmental restructuring	12.5 Adding objects to the environment
W3. Concerns about the detail/duration of website interactions [PPI-C; RR (15); FG]	Brief videos. Digital tools with quick simple recording. Menu bar and search box to enable rapid navigation. Accordion content and a small number of links that provide further information.	Physical opportunity	Environmental restructuring	12.1 Restructuring the physical environment
W4. Reluctance to use a goal setting feature [FG]	Explanation about the potential benefits of goal setting.	Reflective motivation	Persuasion	5.1 Information about health consequences 5.6 Information about emotional consequences
W5. *Family member support* [DR 2.9; FG]	Introductory section that highlights family and friends can assist with using the VKS.	Social opportunity	Enablement	3.1 Social support (unspecified) 12.2 Restructuring the social environment

[a] Codes for the sources are provided in Table S7.

Abbreviations: BCTTv1, Behaviour Change Technique Taxonomy version 1 (14); BCW, Behaviour Change Wheel (13); NHS, National Health Service; NIHR, National Institute for Health and Care Research; TKR, total knee replacement; VKS, Virtual Knee School; W, set of barriers/facilitators to engagement with pre-operative TKR care in a web-based format

Table S9: Behavioural analysis table for engagement with pre-operative TKR education

Set of barriers/*facilitators* to the target behaviour [barrier/facilitator/VKS feature source(s)[a]]	Potential VKS feature(s) that could address the barriers/facilitators	Target component(s) (BCW)	Intervention function(s) (BCW)	Behaviour change technique(s) (BCTTv1)
Ed1. Short length of time between being listed for TKR surgery and undergoing TKR surgery Receiving information immediately after the decision to undergo TKR surgery is made/too far in advance of surgery [RR (7, 16); FG]	Information section that allows all content to be accessed rapidly during any session.	Physical opportunity	Environmental restructuring	12.1 Restructuring the physical environment
Ed2. Low literacy Language barriers *Information presented using methods that address patients' varying health literacy, language abilities and learning styles* [RR (6, 15); DC; FG]	Provide information using simple language, pictures and videos where appropriate. Include a glossary to explain medical terms patients may come across. Provide an option to change the VKS language.	Physical opportunity	Environmental restructuring	12.1 Restructuring the physical environment
Ed3. Reluctance to receive detailed pre-operative information Large volume of information *Desire for detailed information about preparing for TKR surgery and what to expect* [PPI-C; RR (3, 5, 7, 8, 12, 15, 16); DR 1.4–1.20, 1.22–1.25, 1.30, 1.32 – 1.35; DC; FG]	Introductory section that explains the VKS supports users to prepare for TKR surgery and understand what to expect, which can help their recovery after surgery.	Reflective motivation	Persuasion	5.1 Information about health consequences 5.6 Information about emotional consequences
	Information about how to prepare for TKR surgery and what to expect provided through accessible and engaging formats, including:	Physical opportunity	Environmental restructuring	12.1 Restructuring the physical environment

	• brief glossary of medical terms and a more detailed glossary available as a PDF document; • accordion content and a small number of links that provide further information; • checklists e.g. a “traffic light system” checklist about complications and a checklist about home preparations; • videos, including of real people performing practical tasks such as using walking aids, getting in/out of a car, getting up from a fall and going round the supermarket.			
Ed4. Concerns about receiving information about the TKR surgical procedure and/or seeing graphic details of TKR surgery *Desire to understand what happens during TKR surgery* [RR (3); DR (1.13); DC; FG]	Introductory section that explains the VKS will not show graphic details of TKR surgery.	Psychological capability Reflective motivation	Education	5.6 Information about emotional consequences
	Brief text and animation about the TKR surgical procedure that does not show any graphic details of surgery.	Physical opportunity	Environmental restructuring	12.1 Restructuring the physical environment
Ed5. Concerns about finding out about “horror stories” of TKR surgery Concerns about making comparisons with other patients’ experiences of TKR surgery *Desire to find out about other patients’ experiences of TKR surgery* [RR (4, 5); DR 2.4; DC; FG]	Introductory section that: • explains that the VKS provides examples of other patients’ experiences of TKR surgery to help users understand what to expect; • explains that everyone’s preparations and recovery are different.	Psychological capability Reflective motivation	Education Persuasion	5.6 Information about emotional consequences
	Information about TKR surgery provided through appropriately moderated patient stories, which are unlikely to be interpreted as “horror stories”.	Social opportunity Reflective motivation	Persuasion Modelling	6.2 Social comparison 6.3 Information about others’ approval 9.1 Credible source

[a] Codes for the sources are provided in Table S7.
Abbreviations: BCTTv1, Behaviour Change Technique Taxonomy version 1 (14); BCW, Behaviour Change Wheel (13); Ed, set of barriers/facilitators to engagement with pre-operative TKR education; PDF, Portable Document Format; TKR, total knee replacement; VKS, Virtual Knee School

Table S10: Behavioural analysis table for engagement with a pre-operative TKR exercise programme

Set of barriers/*facilitators* to the target behaviour [barrier/facilitator/VKS feature source(s)[a]]	Potential VKS feature(s) that could address the barriers/facilitators	Target component(s) (BCW)	Intervention function(s) (BCW)	Behaviour change technique(s) (BCTTv1)
Ex1. Knee signs and symptoms [PPI-C; DR (2.4, 4.4.2, 4.6); DC; FG]	Flexible exercise programme that includes: • non-weight bearing exercises; • low to moderate intensity exercises; • guidance on how to select exercises, including starting at a relatively easy level and then gradually progressing.	Physical capability Psychological capability Physical opportunity	Education Training Environmental restructuring	1.2 Problem solving 4.1 Instruction on how to perform a behaviour 5.1 Information about health consequences 8.1 Behavioural practice/rehearsal 8.7 Graded tasks 12.1 Restructuring the physical environment
	Patient stories modelling how other patients have successfully performed a pre-operative exercise programme despite severe knee signs and symptoms.	Psychological capability Social opportunity Reflective motivation	Education Persuasion Modelling	5.1 Information about health consequences 6.2 Social comparison 6.3 Information about others' approval 9.1 Credible source
Ex2. Concern that exercising will cause further knee damage [PPI-C; DR (2.4); FG]	Information reassuring users that performing pre-operative exercises is safe for people with severe knee arthritis.	Psychological capability Reflective motivation	Education Persuasion	5.1 Information about health consequences

	Patient stories modelling how other patients have successfully performed a pre-operative exercise programme despite having severe knee arthritis.	Psychological capability Social opportunity Reflective motivation	Education Persuasion Modelling	5.1 Information about health consequences 6.2 Social comparison 6.3 Information about others' approval 9.1 Credible source
Ex3. Being busy with other commitments/distractions Forgetting to exercise [PPI-C; RR (10); FG]	Suggestion about setting exercise reminders, for example on a mobile phone. Optional automated email reminders prompting users to perform exercises, with flexible timing.	Physical opportunity	Environmental restructuring	7.1 Prompts/cues
	Information about the benefits of integrating exercise into daily routines (habit formation) and suggestions about how to do so.	Psychological capability Reflective motivation Automatic motivation	Education Persuasion Training	4.1 Instruction on how to perform a behaviour 8.1 Behavioural practice/rehearsal 8.3 Habit formation
Ex4. Other health issues [PPI-C; DC; FG]	Brief information about exercising with specific health conditions.	Psychological capability	Education	5.1 Information about health consequences
	Flexible exercise programme that includes: • non-weight bearing exercises; • low to moderate intensity exercises.	Physical capability Psychological capability Physical opportunity	Education Training Environmental restructuring	1.2 Problem solving 4.1 Instruction on how to perform a behaviour 5.1 Information about health consequences 12.1 Restructuring the physical environment
	Guidance on seeking health professional advice about other health issues that may present a barrier to exercise.	Social opportunity	Enablement	3.2 Social support (unspecified) 9.1 Credible source
Ex5. Lack of access to specific equipment or facilities [FG]	Flexible exercise programme that includes exercises that do not require non-household equipment or facilities.	Physical opportunity	Environmental restructuring	12.1 Restructuring the physical environment

Ex6. Belief that pre-operative exercises are not important/beneficial *Beliefs about the benefits of pre-operative exercise, including on post-operative recovery* *Sense of personal responsibility for own recovery* [PPI-C; (5, 10); DR (1.4, 1.5, 2.4); DC; RR FG]	Introductory and exercise sections that explain the potential benefits of pre-operative exercise, including for post-operative recovery. Explanations about the benefits of specific exercises/reasons for specific exercises. Guidance to support users identify their reasons for wanting to exercise pre-operatively.	Psychological capability Reflective motivation	Education Persuasion	1.2 Problem solving 5.1 Information about health consequences 5.6 Information about emotional consequences
	Information explaining that experts agree pre-operative exercise is beneficial (based on the NICE guidelines).	Reflective motivation	Persuasion	6.3 Information about others' approval 9.1 Credible source
	Patient stories modelling how other patients have performed and benefitted a pre-operative exercise programme.	Psychological capability Social opportunity Reflective motivation	Education Persuasion Modelling	5.1 Information about health consequences 5.6 Information about emotional consequences 6.2 Social comparison 6.3 Information about others' approval 9.1 Credible source
Ex7. Lack of guidance on performing a pre-operative exercise programme *Guidance on performing a pre-operative exercise programme* [DC; FG]	Flexible exercise programme that includes: • guidance on how to select and progress exercises; • videos of relatable patient representatives demonstrating how to perform exercises, with appropriate audio explanations of the exercises.	Psychological capability Social opportunity	Education Training Modelling	1.2 Problem solving 4.1 Instruction on how to perform a behaviour 5.1 Information about health consequences 6.1 Demonstration of the behaviour 6.2 Social comparison 8.1 Behavioural practice/rehearsal 8.7 Graded tasks

	Tips on exercising from peers	Psychological capability Social opportunity Reflective motivation	Education Modelling	4.1 Instruction on how to perform the behaviour 6.2 Social comparison 6.3 Information about others' approval 9.1 Credible source
Ex8. Dislike of certain exercise types or formats *Preference for certain exercise types or formats* [FG]	Explanations about the benefits of specific exercises/reasons for specific exercises.	Psychological capability Reflective motivation	Education Persuasion	5.1 Information about health consequences 5.6 Information about emotional consequences
	Guidance to support users to identify and perform other types of exercise they enjoy alongside the VKS exercise programme.	Psychological capability Reflective motivation	Education Persuasion	1.2 Problem solving 4.1 Instruction on how to perform a behaviour 5.6 Information about emotional consequences
Ex9. Setting exercise goals and not meeting them *Setting exercise goals, reviewing exercise goals and receiving feedback about exercise goals* [PPI-C; DR (1.6, 4.12); DC; FG]	Exercise goal setting, review and feedback feature that includes: • information about goal setting, including its benefits and how to set achievable goals; • suggestions about how to adapt goals if they are not met; • encouraging feedback; • goal setting and recording sheet that users can download and print out.	Psychological capability Physical opportunity Reflective motivation	Education Persuasion Environmental restructuring Enablement	1.1 Goal setting (behaviour) 1.2 Problem solving 1.4 Action planning 1.5 Review behaviour goal(s) 1.6 Discrepancy between current behaviour and goal 2.2 Feedback on behaviour 2.3 Self-monitoring of behaviour 5.1 Information about health consequences 10.4 Social reward 12.5 Adding objects to the environment
Ex10. *Monitoring exercise completion* [FG]	Guidance on monitoring exercise completion.	Physical opportunity	Environmental restructuring Enablement	2.3 Self-monitoring of behaviour

	Exercise diary that users can download and print out. Private online personal exercise diary.	Reflective motivation		12.5 Adding objects to the environment
Ex11. *Family member support* [RR (17)]	Explanation that some patients find it helpful to exercise with family members or friends.	Social opportunity	Enablement	3.1 Social support (unspecified) 12.2 Restructuring the social environment

[a] Codes for the sources are provided in Table S7.

Abbreviations: BCTTv1, Behaviour Change Technique Taxonomy version 1 (14); BCW, Behaviour Change Wheel (13); Ex, set of barriers/facilitators to engagement with a pre-operative TKR exercise programme; NICE, National Institute for Health and Care Excellence; VKS, Virtual Knee School

Table S11: Behavioural analysis table for engagement with healthy lifestyle changes

Set of barriers/*facilitators* to the target behaviour [barrier/facilitator/VKS feature source(s)[a]]	Potential VKS feature(s) that could address the barriers/facilitators	Target component(s) (BCW)	Intervention function(s) (BCW)	Behaviour change technique(s) (BCTTv1)
Healthy lifestyle change: increase physical activity and reduce sedentary behaviour[b]				
HL1. Knee signs and symptoms Fatigue Poor physical fitness [PPI-C; RR (10, 11); DR (2.4); FG]	Information about the potential benefits of non-weight bearing activities and examples of non-weight bearing activities.	Physical capability Reflective motivation	Education	5.1 Information about health consequences
	Information about the potential benefits of activity pacing and guidance on how to pace activities. Activity planning sheet that users can download and print out.	Physical capability Physical opportunity Psychological capability Reflective motivation	Education Training Environmental restructuring	1.2 Problem solving 1.4 Action planning 4.1 Instruction on how to perform a behaviour 5.1 Information about health consequences 8.7 Graded tasks 12.5 Adding objects to the environment
	Information about the potential benefits of using walking aids and videos of real people demonstrating how to use walking aids.	Physical capability Psychological capability Social opportunity Reflective motivation	Education Training Modelling Enablement	4.1 Instruction on how to perform a behaviour 5.1 Information about health consequences 6.1 Demonstration of the behaviour 6.2 Social comparison 12.6 Body changes (assistive aids)
	Information about the potential benefits of using analgesics and the importance of taking them regularly as advised by the user's care team.	Physical capability Reflective motivation	Education	5.1 Information about health consequences

	Information about the potential benefits of using cushioned soles/insoles.	Physical capability Reflective motivation	Education	5.1 Information about health consequences
	Patient stories modelling how other patients have successfully increased their activity levels/reduced their sedentary behaviour despite severe knee signs and symptoms, fatigue and poor physical fitness.	Psychological capability Social opportunity Reflective motivation	Education Persuasion Modelling	5.1 Information about health consequences 6.2 Social comparison 6.3 Information about others' approval 9.1 Credible source
HL2. Forgetfulness [RR (11)]	Guidance on setting activity reminders, for example on a mobile phone.	Physical opportunity	Environmental restructuring	7.1 Prompts/cues
	Information about the benefits of habit formation and suggestions about how to make being more active/less sedentary a habit.	Psychological capability Reflective motivation Automatic motivation	Education Persuasion Training	4.1 Instruction on how to perform a behaviour 8.1 Behavioural practice/rehearsal 8.3 Habit formation
HL3. Fear of falling [RR (11)]	Guidance to support users to choose activities that users are likely to be able to do with minimal risk of falling.	Psychological capability Reflective motivation	Education Persuasion	1.2 Problem solving 5.1 Information about health consequences
HL4. Other health issues [RR (11)]	Guidance on seeking health professional advice about other health issues that may present a barrier to being more active/less sedentary.	Social opportunity	Enablement	3.2 Social support (unspecified) 9.1 Credible source
HL5. Social and environmental circumstances (including lack of time, social responsibilities/ commitments, going on holiday and finding it difficult to do physical activities in the evening or in certain weather conditions)	Guidance to support users to identify barriers to being more active/less sedentary and strategies for addressing the barriers.	Psychological capability Reflective motivation	Education	1.2 Problem solving 1.4 Action planning

[RR (11)]				
HL6. *Beliefs about the benefits of being more active/less sedentary* *Sense of achievement* [RR (11)]	Explanations about the benefits of and reasons for being more active/less sedentary. Guidance to support users identify their reasons for wanting to be more active/less sedentary.	Psychological capability Reflective motivation	Education Persuasion	1.2 Problem solving 5.1 Information about health consequences 5.6 Information about emotional consequences
	Patient stories modelling how other patients have benefitted from being more active/less sedentary.	Psychological capability Social opportunity Reflective motivation	Education Persuasion Modelling	5.1 Information about health consequences 5.6 Information about emotional consequences 6.2 Social comparison 6.3 Information about others' approval 9.1 Credible source
HL7. *Enjoyment of certain activities* [RR (11)]	Guidance to support users to identify/perform physical activities they enjoy.	Psychological capability Reflective motivation	Education Persuasion	1.2 Problem solving 4.1 Instruction on how to perform a behaviour 5.6 Information about emotional consequences
HL8. *Self-reflection on sedentary time/activity levels* [RR (11)]	Guidance to support users to monitor and reflect on their current activity levels/sedentary behaviour, identify barriers to being more active/less sedentary and identify strategies for addressing the barriers.	Psychological capability Reflective motivation	Education Enablement	1.2 Problem solving 1.4 Action planning 2.3 Self-monitoring of behaviour
	Sedentary behaviour/physical activity screening feature that provides personalised feedback.	Reflective motivation	Persuasion	2.2 Feedback on behaviour 5.1 Information about health consequences
HL9. Activity goals perceived as futile or pointless Setting too challenging goals	General guidance on goal setting, including setting challenging but achievable goals and adapting goals if they are not met.	Psychological capability	Education	1.1 Goal setting (behaviour) 1.2 Problem solving 1.4 Action planning

Setting challenging but achievable goals [RR (11)]	Exercise goal setting, review and feedback feature that includes: • information about goal setting, including its benefits and how to set achievable goals; • an option to set a goal about another type of physical activity, in addition to the VKS exercise programme; • suggestions about how to adapt goals if they are not met; • encouraging feedback; • goal setting and recording sheet that users can download and print out.	Psychological capability Physical opportunity Reflective motivation	Education Persuasion Environmental restructuring Enablement	1.1 Goal setting (behaviour) 1.2 Problem solving 1.4 Action planning 1.5 Review behaviour goal(s) 1.6 Discrepancy between current behaviour and goal 2.2 Feedback on behaviour 2.3 Self-monitoring of behaviour 5.1 Information about health consequences 10.4 Social reward 12.5 Adding objects to the environment
HL10. Issues with monitoring activity using a pedometer *Monitoring physical activity* [RR (11); FG]	Guidance on self-monitoring activity levels/sedentary behaviour, including signposting to an activity tracking app that users can download on a mobile phone.	Reflective motivation	Enablement	2.3 Self-monitoring of behaviour
Healthy lifestyle change: improve weight management and diet				
HL11. Lack of guidance on weight management [DR (1.27); DC; FG]	Guidance on weight management strategies.	Psychological capability	Education	4.1 Instruction on how to perform the behaviour 5.1 Information about health consequences
	Signposting to credible websites that provide weight management advice.	Psychological capability	Education	5.1 Information about health consequences 9.1 Credible source
HL12. Other health issues or lifestyle choices [FG]	Signposting to credible websites that provide weight management advice that accounts for other health issues or lifestyle choices.	Psychological capability	Education	5.1 Information about health consequences 9.1 Credible source

	Guidance on seeking health professional advice about other health issues that may present a barrier to weight management.	Social opportunity	Enablement	3.2 Social support (unspecified) 9.1 Credible source
HL13. Difficulty adhering to diets (including due to a tendency to overeat) [FG]	Guidance to support users to identify barriers to adhering to diets and strategies for addressing the barriers.	Psychological capability Reflective motivation	Education	1.2 Problem solving 1.4 Action planning
HL14. *Beliefs about the benefits of healthy eating and weight management, including on post-operative recovery* *Sense of personal responsibility for own recovery* [RR (5); DR (1.4); FG]	Explanations about the benefits of/reasons for healthy eating and weight management, including on post-operative recovery. Guidance to support users identify their reasons for wanting to lose weight.	Psychological capability Reflective motivation	Education Persuasion	1.2 Problem solving 5.1 Information about health consequences 5.6 Information about emotional consequences
	Patient stories modelling how other patients have benefitted from managing their weight.	Psychological capability Social opportunity Reflective motivation	Education Persuasion Modelling	5.1 Information about health consequences 5.6 Information about emotional consequences 6.2 Social comparison 6.3 Information about others' approval 9.1 Credible source
HL15. *Monitoring eating habits* [FG]	Guidance on self-monitoring eating habits, including signposting to an app that can be used to track eating habits.	Reflective motivation	Enablement	2.3 Self-monitoring of behaviour
Healthy lifestyle change: reduce alcohol consumption				
HL16. Environmental circumstances (including going on holiday pre-operatively) [FG]	Guidance to support users to identify barriers to reducing their alcohol consumption and strategies for addressing the barriers.	Psychological capability Reflective motivation	Education	1.2 Problem solving 1.4 Action planning
HL17. Older age/being retired, potentially leading boredom; a tendency to be less risk-averse; being more affluent; feeling lonely; considering	Guidance to support users to identify barriers to reducing their alcohol consumption and strategies for addressing the barriers.	Psychological capability Reflective motivation	Education	1.2 Problem solving 1.4 Action planning

themselves too old to change their drinking habits and not wanting to be 'educated' about alcohol use. *Older age, potentially leading to greater motivation to look after their health and a tendency to be more open and honest about their drinking habits* [RR (12)]				
HL18. Not perceiving excess alcohol consumption as an issue/not perceiving themselves a 'risky' or 'problem' drinker/being defensive about drinking habits 'Risky drinking' sounding appealing Alcohol consumption being a sensitive subject Not understanding the terms 'standard drink' and/or 'unit' *Being open and honest about drinking habits (linked to being older, a patient and/or male)* [RR (12)]	Information about alcohol consumption guidelines and the risks of excess alcohol consumption/benefits of reducing alcohol consumption presented clearly and sensitively, including: • not using the terms 'risky drinking', 'risky drinker' or 'problem drinker'; • using terms such as 'pint of beer' and 'glass of wine'. Infographic explaining standard drinks.	Psychological capability Physical opportunity Reflective motivation	Education Persuasion	5.1 Information about health consequences 5.6 Information about emotional consequences 12.1 Restructuring the physical environment
HL19. Not understanding the impact of pre-operative alcohol consumption on outcomes of TKR surgery *Desire to have TKR surgery*	Information about the risks of excess alcohol consumption/ benefits of reducing alcohol consumption, including on post-operative recovery and weight.	Psychological capability Reflective motivation	Education Persuasion	1.2 Problem solving 5.1 Information about health consequences 5.6 Information about emotional consequences

Beliefs about the benefits of reducing alcohol consumption, including on post-operative recovery and weight *Sense of obligation to prepare for TKR surgery and help ensure it goes well* [RR (12)]	Guidance to support users to identify their reasons for wanting to reduce their alcohol consumption.			
	Patient stories modelling how other patients have benefitted from reducing their pre-operative alcohol consumption.	Psychological capability Social opportunity Reflective motivation	Education Persuasion Modelling	5.1 Information about health consequences 5.6 Information about emotional consequences 6.2 Social comparison 6.3 Information about others' approval 9.1 Credible source
HL20. Not realising how much alcohol they are consuming *Identifying and reflecting on their alcohol consumption* [RR (12)]	Guidance to support the user to monitor and reflect on their current alcohol consumption, identify barriers to reducing their alcohol consumption and identify strategies for addressing the barriers.	Psychological capability Reflective motivation	Education Enablement	1.2 Problem solving 1.4 Action planning 2.3 Self-monitoring of behaviour
	Alcohol consumption screening feature that provides personalised feedback.	Reflective motivation	Persuasion	2.2 Feedback on behaviour 5.1 Information about health consequences

[a] Codes for the sources are provided in Table S7.

[b] Only includes details related to increasing physical activity in general rather than engaging in a pre-operative TKR exercise programme.

Abbreviations: BCTTv1, Behaviour Change Technique Taxonomy version 1 (14); BCW, Behaviour Change Wheel (13); HL, set of barriers/facilitators to engagement with healthy lifestyle changes; TKR, total knee replacement; VKS, Virtual Knee School

Table S12: Behaviour change techniques employed in the potential Virtual Knee School features

Cluster[a]	Behaviour change technique[a]
1. Goals and planning	1.1 Goal setting (behaviour)
	1.2 Problem solving
	1.4 Action planning
	1.5 Review behaviour goal(s)
	1.6 Discrepancy between current behaviour and goal
2. Feedback and monitoring	2.2 Feedback on behaviour
	2.3 Self-monitoring of behaviour
3. Social support	3.1 Social support (unspecified)
4. Shaping knowledge	4.1 Instruction on how to perform a behaviour
5. Natural consequences	5.1 Information about health consequences
	5.6 Information about emotional consequences
7. Comparison of behaviour	6.1 Demonstration of the behaviour
	6.2 Social comparison
	6.3 Information about others' approval
7. Associations	7.1 Prompts/cues
8. Repetition and substitution	8.1 Behavioural practice/rehearsal
	8.3 Habit formation
	8.7 Graded tasks
9. Comparison of outcomes	9.1 Credible source
10. Reward and threat	10.4 Social reward
12. Antecedents	12.1 Restructuring the physical environment
	12.2 Restructuring the social environment
	12.5 Adding objects to the environment
	12.6 Body changes (assistive aids)
15. Self-belief	15.1 Verbal persuasion about capability

[a] Clusters and behaviour change techniques are from the Behaviour Change Technique Taxonomy (v1) (14).

Table S13: Additional behaviour change techniques identified in the review by Safari et al. (18)

Cluster[a]	Behaviour change technique[a]
1. Goals and planning	1.7 Review outcome goals
2. Feedback and monitoring	2.4 Self-monitoring of outcome(s) of behaviour
	2.6 Biofeedback
3. Social support	3.2 Social support (practical)
	3.3 Social support (emotional)
4. Shaping knowledge	4.2 Information about antecedents
5. Natural consequences	5.4 Monitoring of emotional consequences
	5.5 Anticipated regret
9. Comparison of outcomes	9.2 Pros and cons
11. Regulation	11.2 Reduce negative emotions
12. Antecedents	12.4 Distraction
15. Self-belief	15.4 Self-talk
16. Covert learning	16.2 Imaginary reward
	16.3 Vicarious consequences

[a] Clusters and behaviour change techniques are from the Behaviour Change Technique Taxonomy (v1) (14). The behaviour change techniques were identified in a systematic review of digital-based structured osteoarthritis self-management programmes by Safari et al. (18) but were not employed in any of the potential VKS features.

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Supplementary File 3: Phase 4 findings supporting information

Table S14: Virtual Knee School prototype summary

Section	Page(s)[a]	Level	Key features[b]
Login	*'Sign up to the Virtual Knee School'*	N/A	Sign up process that involved entering an email address, password and participant identification number and completing a CAPTCHA verification.
	'Login'	N/A	Login process that involved entering an email address and password. Reset password option.
Main	*'Welcome'* (homepage)	1	Brief text summarising the VKS purpose. Picture buttons to the other three level 1 pages.
	'Help'	N/A	Text and accordion content explaining how to use the VKS/overcome problems users may encounter when using the VKS.
	'Contact us'	N/A	Text providing the VKS email address.
	Footer pages	N/A	Privacy and cookies policy, accessibility statement, links to other helpful websites.
	All pages	N/A	Header with *'Help'* and *'Log out'* buttons. Footer containing links to the footer pages, XXX terms of use and the user's most viewed pages. Meganav and search box. Breadcrumb trail (not shown on the homepage). *'Print this page'* button (not shown on the homepage). Accessibility toolbar that allows users to change the VKS language, text size and contrast (automatically open but can be opened and closed by selecting the toolbar header).
Introductory	*'About the Virtual Knee School'* (introductory menu)	1	Picture buttons to both level 2 introductory pages. Text and an image explaining how to use the accessibility toolbar. Welcome video designed to address key barriers to engagement with the VKS and its target behaviours. Text navigation instructions.
	'Virtual Knee School development and team'	2	Text providing a brief overview of the VKS development. PDF of the Phase 1b modified Delphi study final recommendations (1). Names, photographs and brief biographies of key research team members.

			Names of the additional research team members and the PAG PPI members.
	'Common questions'	2	Accordion content with answers to questions about the VKS and how to use it.
Education	*'Information for your operation'* (education menu)	1	Picture buttons to all three level 2 education pages.
	'What to expect'	2	Picture buttons to all seven level 3 expectations subpages.
	Seven expectations subpages	3	Text/accordion content covering TKR surgery; what to expect before, during and after the hospital stay; risks of TKR surgery; a brief list of medical terms; and patients' knee replacement stories. Knee joint anatomy image, PDF list of medical terms and five educational videos.
	'Preparing for your operation'	2	Picture buttons to all seven level 3 preparing subpages.
	Seven preparing subpages	3	Text/accordion content covering managing knee pain; healthy lifestyle changes; goal setting; walking aids and other equipment; making practical preparations; return to work planning; and patients' preparation stories. PDF exercise goal-setting/recording sheet, two educational videos and 10 walking aid videos.
	'Recovering from your operation'	2	Picture buttons to all six level 3 recovering subpages.
	Six recovering subpages	3	Text/accordion content covering strategies for improving post-operative recovery; managing concerns (including a traffic light checklist); post-operative mobilisation, returning to usual activities and travelling; and patients' recovery stories. Three educational videos and 10 walking aid videos.
Exercise	*'Your exercise plan'* (exercise menu)	1	Picture buttons to all five level 2 exercise pages. Text covering benefits of exercising pre-operatively, guidance about the VKS exercise programme and essential safety information.
	'About the Virtual Knee School exercise plan'	2	Text covering key questions and answers about the VKS exercise programme, including potential concerns and safety considerations.
	'Tips for sticking to your exercise plan'	2	Text covering goal setting, self-monitoring exercise completion, habit formation, identifying reasons for wanting to exercise and setting exercise reminders. PDF exercise goal-setting/recording sheet and PDF exercise diary.
	'Patients' exercise stories'	2	Two patient stories modelling how patients have successfully overcome barriers to and benefited from exercising pre-operatively.

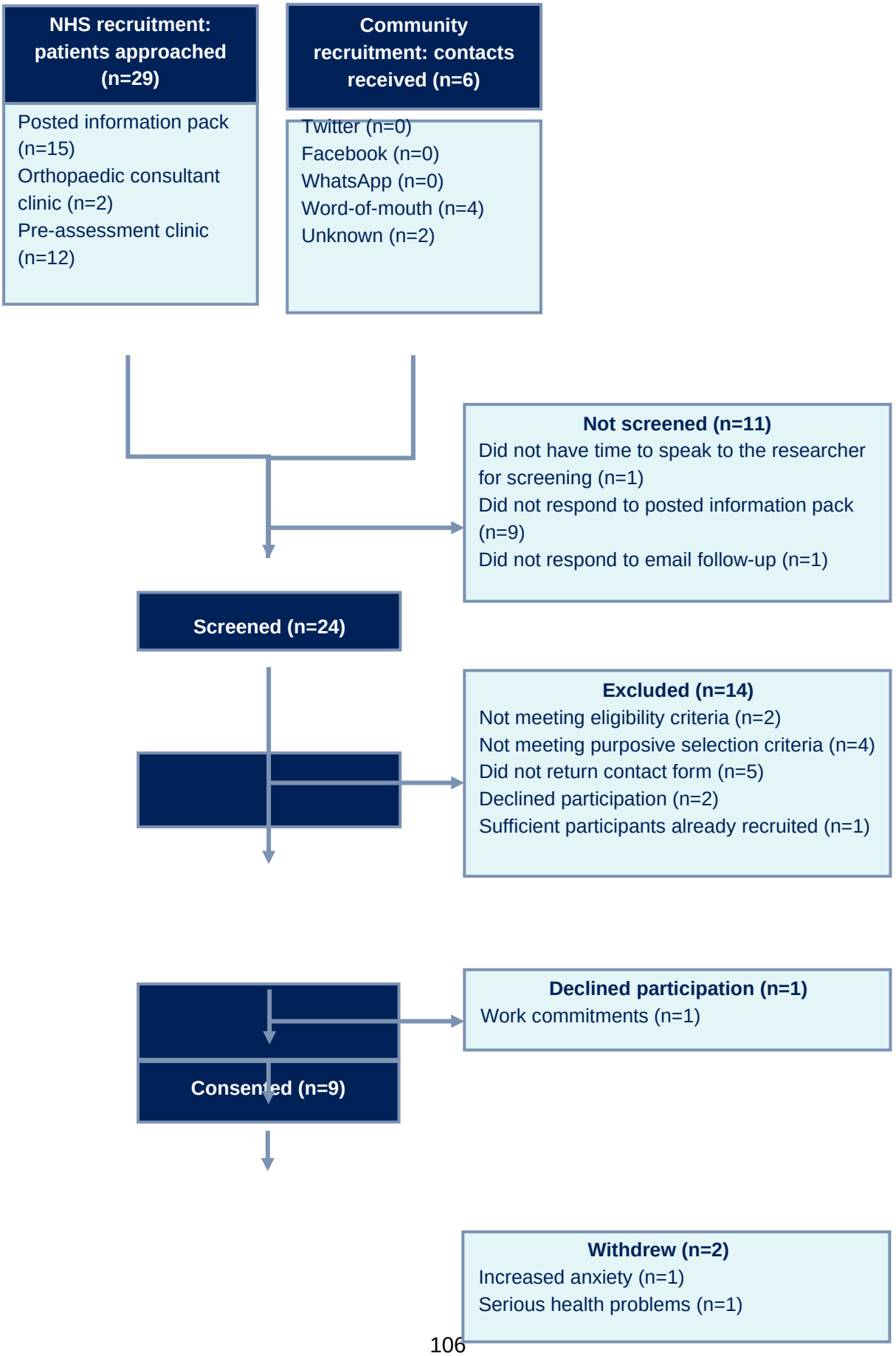
	'Your exercise goals'	2	Text explaining the benefits of goal setting. PDF exercise goal-setting/recording sheet and PDF exercise diary. Buttons to set new goals and view current goals. Dated list of goals with options to edit goals and review goals/edit review.
	Four exercise goal subpages	3	Goal setting form that includes two VKS exercise goals (required) and a personal exercise goal (optional). Text summarising the goals set. Goal review form with *'Yes'*, *'Partly'* and *'No'* options for each goal set. Goal feedback that is personalised based on the goal review form responses, with tips on how the user could adapt/progress their goals.
	'Carry out an exercise session'	2	Text advising users to view the *'Your exercise plan'* and *'About the Virtual Knee School' exercise plan'* pages before performing an exercise session, with hyperlinks to both pages. Text providing guidance on how to perform an exercise session. Fifteen exercise videos organised in five categories, with text explaining the benefits of each exercise category. PDF exercise booklet.

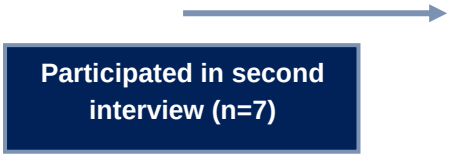
[a] Text in italics in single quotation marks is the page name displayed in the website banner.

[b] All static images were accompanied by PDF documents and all videos were accompanied by transcripts/a booklet for accessibility.

Abbreviations: CAPTCHA, Completely Automated Public Turing test to tell Computers and Humans Apart; PAG, Project Advisory Group; PDF, Portable Document Format; PPI, Patient and Public Involvement; TKR, total knee replacement; VKS, Virtual Knee School

Figure S1: Think-aloud interview participant flow chart





NHS, National Health Service

Table S15: Think-aloud interview participant characteristics

	Number of participants (%) (n=9)
Age (years)	
40–49	1 (11)
50–59	1 (11)
60–69	3 (33)
70–79	3 (33)
80-89	1 (11)
Gender	
Female	3 (33)
Male	6 (67)
Experience of TKR	
Pre	3 (33)
Post	4 (44)
Pre, post	2 (22)
Confidence in using the Internet	
Very confident	2 (22)
Confident	3 (33)
Neither confident nor unconfident	2 (22)
Unconfident	2 (22)
Indication for TKR[a]	
Osteoarthritis	9 (82)
Rheumatoid arthritis and osteoarthritis	2 (18)
Location of TKR[a]	
NHS hospital	10 (91)
Private hospital	1 (9)
Months since previous TKR[b]	
<3	3 (50)
3<6	2 (33)
6<12	1 (17)
Body mass index (kg/m²)	
18.5<25	2 (22)
25<30	1 (11)
30<40	3 (33)
≥40	3 (33)
Ethnicity	
White British	7 (78)
Indian	1 (11)
African Caribbean	1 (11)
Disability or health condition that could affect ability to use a website or carry out gentle exercises[c]	
Dyslexia and dyspraxia	1 (11)
Visual impairment	2 (22)
Hand pain/swelling	1 (11)

Living location	
Yorkshire and the Humber	8 (89)
Scotland	1 (11)
Highest educational qualification	
None	2 (22)
Apprenticeship	1 (11)
Vocational qualification (or equivalent)	3 (33)
Undergraduate degree	3 (33)
Current employment status	
Employed full-time	1 (11)
Employed part-time	1 (11)
Retired	6 (67)
Medically disabled	1 (11)

[a] Participants who were both awaiting and had undergone TKR were counted twice (11 TKRs in total).
[b] Only includes participants who had previously undergone TKR (n=6).
[c] Participants could report more than one option.
Abbreviations: NHS, National Health Service; Post, previously undergone TKR; Pre, listed for TKR; TKR, total knee replacement

Table S16: Example quotes for issues identified with the Virtual Knee School prototype

VKS prototype section/aspect	Issues	Example quotes[a]
Design and overall content	Not realising it was possible to select the accordions (expandable headings).	“No, no, that [option to select the accordion] weren't obvious, no.” (Vera)
	Feeling there was too much text.	"There’s a lot of information, a lot of reading, I’m more for flipping through as quick as I can as I’ve said, and there is a lot of information on the pages.” (Laurence)
	Having difficulty locating and/or using the accessibility toolbar.	“Well, it [accessibility toolbar] is good for people who are very literate, fluent in computer and anything it’s alright, but I'm at the creeping stage. […] I’m still bottle fed.” (Zuri)[b]
	Being concerned about whether there was enough time to watch the videos.	“I didn’t know whether I would have enough time to watch the whole video.” (Haaniya)
	Believing the patient stories were from real-life patients.	“I assumed, even with that [text] actually, that these were really people.” (Naomi)[b]
Information architecture and navigation	Finding the tunnelling to the introductory section menu unhelpful/confusing.	“Well, I think when you open any website, it should take you to the homepage. […] Because that’s the starting point, the homepage is the starting point, the homepage tells you what the website’s, what the content of the website is.” (Glen)
	Feeling overwhelmed by the volume of content due to the education dropdown menu displaying the titles of all 24 education pages/subpages.	“…too many categories there for me, I don’t know what…I mean, they might be all little tiny bits, I’ll go to the first one, let’s have a look about…” (Laurence)
	Not realising it was possible to select the small triangles to display lower-level pages when using the meganav on a mobile device in portrait orientation.	“But then when I clicked on the arrow on information for your operation, it brought up the other menu. And then recovering. So and then it brings up the other menu. I didn’t realise that was there.” (Ella)
	Feeling confused by the back and next buttons both going to the same page if the user accessed the last page in a section from the section menu.	“Well, first impression was it was a bit confusing because it’s basically taking you to the same place […]” (Glen)
	Feeling extra hyperlinks would be useful for quickly checking other pages, and feeling confused about whether words in bold were hyperlinks.	“So if you click on those highlighted, presumably, can you get more about that, or is that just bold?” (Naomi)[b]

Login section	Mistyping characters leading to the two passwords entered on the sign-up page not matching or the password entered on the login page being incorrect.	“These passwords do not match. […] On my phone I can press a button and I can actually read them. That’s what I’m used to.” (Arthur)
Main section	Feeling the main homepage did not make it clear that the website had three main sections.	“Well, what I will say is if I was on your homepage now, I personally, I can only speak personally, I don’t think it would be obvious to me that this website had beyond the homepage three key sections.” (Glen)
	Feeling it should be clearer that the website provides information related to the peri- and post-operative phases, rather than just the pre-operative phase.	“Well, I think you should make it very clear that it’s covering every aspect, you know? Leading up to it, during and after.” (Glen)
	Feeling the three homepage picture buttons did not indicate where to find the information the user wanted.	“But it’s…they’re not really telling me…like the knee joint, can I see a knee joint, it doesn’t tell me on those where I’m going to find it if you know what I mean.” (Laurence)
	Feeling a link to the *‘Contact us’* page should be included in the website footer for consistency with other websites.	“Maybe the *‘Contact us’* as well could also be down here [in the website footer]. Because on most websites it’s usually at the bottom of the page.” (Ella)
	Considering using the VKS email address to ask questions about the user’s own operation.	“I’m thinking I might ask something about my knee operation, possibly. Or if there was anything I couldn’t quite understand on the School, you know, on the actual pages.” (Arthur)
Introductory section	Feeling there was too much information on the introductory section menu.	"I think there’s a lot of information, like you can change the colour of the background. There’s a lot of information to process; for me I don’t think I would change the colour of the background but if other people wanted to, they could.” (Jessica)
	Feeling confused by the instructions on how to use the website.	"I found it a little bit confusing, only for, there seemed to be a lot of information there, so, it’s hard to explain. Because it seemed to be kind of repeating itself a little bit over, on the, on the second one.” (Ella)
	Finding the PDF of the Phase 1b modified Delphi study recommendations too detailed and *“very confusing”.*	“I think it's a lot of information. Maybe too much. I'm just, it's very confusing. Because to me this this ,like this section here for instance. I expected to be able to click on.” (Ella)
	Feeling it would be helpful to amend the wording of certain answers on the *‘Common questions’* page.	“And you can say that it relieves stiffness as well. Because exercise definitely relieves stiffness.” (Haaniya)

	Feeling it would be helpful to cover what to do if the user has bilateral knee problems on the *'Common questions'* page.	"Now, whether that's something that you can think about and, you know, have a line saying, somebody says I have, you know, I've got a problem with both knees but I'm having one of them done first sort of thing, does that change the way I approach anything?" (Glen)
Education section	Requesting further information about specific topics.	It's leading me to ask more questions a bit now. I'm wanting…because they're obviously going to do my second knee, one guy said about six weeks after the first one. How long…I would need to find out roughly how long it takes for the scar to heal enough to get back to exercising in the pool, that's something I don't know actually." (Laurence)
	Feeling the *'Goal setting'* page should provide more encouragement for users who do not meet their goals.	"I think it should say to encourage the people who, even if you don't meet your goals and you think you… not to be disappointed but to carry on at your own level and what you can achieve, rather than be upset with what you've not achieved, not to get disheartened." (Haaniya)
	Wanting post-operative goals to look forward to and *"something visual".*	"So maybe if there's something visual there that would possibly put that thought into somebody's head, you know, look forward to this kind of goal." (Ella)
Exercise section	Feeling confused about whether the exercise section was for the pre- or post-operative phase.	"It was just how I'd read it with the recovery afterwards. Sorry about the message that came up. Yeah, it's the way that it says it can manage your pain before your operation and recover faster afterwards. It was just my mind thinking it was for afterwards too." (Ella)
	Highlighting queries or concerns about specific aspects of the exercise section text.	"It [at least two exercise sessions a week] doesn't sound enough really." (Arthur)
	Thinking the exercise category titles related to the videos above them rather than below them.	"But I think it's the way I had it, because if you look, that's category 1 and there's no […] no break in between, is there?" (Jessica)
	Missing the *'Submit'* button on the goal-setting and review forms.	"I used to be observant when I was younger but I'm not as observant as I should be and I just didn't spot the submit button." (Glen)
	Entering numbers in the goal-setting form as words rather than numerals.	"Oh, you've got to enter a number." (Glen)
	Finding it challenging to set appropriate exercise goals due to unfamiliarity with the VKS exercise programme.	"How many different exercises? Well, I only can walk, so it's just one then, isn't it? […] It will make a bit more sense after we've seen that [Virtual Knee School exercise plan]." (Jessica)

[a] The participants were interviewed in the following order: Ella, Jessica, Glen, Arthur, Vera, Haaniya, Laurence, Naomi, Zuri. There are a larger number of quotes from the first few participants because issues were identified and addressed on an iterative basis. Unless otherwise indicated, the quotes are from participants who used the VKS prototype prior to the change(s) detailed in Table 6 being made to address the issue.

[b] Quote is from a participant who used the VKS prototype after the change(s) detailed in Table 6 were made to address the issue, suggesting the issue was not fully resolved.

Abbreviations: PDF, Portable Document Format; VKS, Virtual Knee School

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