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REVIEW ARTICLE

"Wearable Sensors to Guide Remote Rehabilitation Following Knee Arthroplasty Surgery"

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Abstract

Background Total knee arthroplasty requires effective rehabilitation to achieve optimal results, but institutions often rely on unsupervised home exercises due to cost constraints. Wearable sensors have become increasingly popular as a potential method of monitoring patients remotely to ensure efficacy and compliance. This review assesses the current evidence for their use in remotely monitored rehabilitation following knee arthroplasty.

Methods A systematic review of the literature from 1st January 2000 to 17th February 2022 was undertaken. Devices were categorised as joint-specific or physical activity sensors. Studies were classified as those providing remotely supervised rehabilitation as an additional or as an alternative intervention.

Results Remotely supervised rehabilitation using wearable sensors demonstrated similar outcomes when provided as an alternative to standard care in most studies. One group found improved outcomes for knee-specific sensors compared with standard care. There were improved physical activity and healthcare resource use outcomes described in the literature where sensors were used in addition to standard care.

Discussion This review found evidence for the use of wearable sensors in remotely supervised rehabilitation following knee arthroplasty surgery. This included methodological heterogeneity, differing definitions of standard care, and variable follow-up periods. Robust randomised control trial data with a longer follow-up period are needed.

Keywords Knee arthroplasty · Knee replacement · Remote rehabilitation · Wearable sensors · Telerehabilitation

Introduction

Total knee arthroplasty (TKA) is a highly successful and cost-effective treatment for end-stage arthritis. It is becoming increasingly popular with changes in population demographics and quality of life expectations [1]. There will be an estimated increase of 76,497 to 118,666 TKAs in the UK from 2012 to 2035, and a 600% increase in TKA figures in the US over a period of 25 years [1, 2] with similar trends across Asia. Over 100,000 were performed in the UK in 2019 [3]. Despite this, patient dissatisfaction rates are around 20% with few reporting a completely problem-free TKA [4].

Adequate postoperative rehabilitation is vital to ensure optimal outcomes but there is a lack of consensus with respect to the protocols used [5]. Annual US national spending on rehabilitation following TKA is reported to be almost $500 million and is the source of the greatest variation in costs [6, 7]. Length of stay following TKA is reducing due to multimodal enhanced recovery protocols and, therefore, there is increased emphasis on the delivery of outpatient rehabilitation [8]. Extended in-person outpatient physiotherapy shows significant improvements in both function and patient-reported outcome measures (PROMs) but with an associated increase in healthcare resource use [9, 10]. In contrast, home-based physiotherapy is far less resource-intensive but compliance with unsupervised physiotherapy is generally poor [11]. Expert consensus recommends directly

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supervised post-operative rehabilitation following TKA but over 25% of high-volume UK National Health Service (NHS) orthopaedic centres do not provide this [10, 12].

Remote patient monitoring using wearable sensors following arthroplasty has recently gained considerable interest [13]. It has the potential to provide healthcare professionals with reliable, objective information to monitor compliance, guide adjustments to rehabilitation and identify patients who require more intensive input. Wearable sensors also offer bespoke rehabilitation for patients based on their individual expectations and goals. They provide a means for two-way communication between the clinical team and the patient and can allow for objective data on pain and function to be captured. This empowers patients to take control of their rehabilitation. Telerehabilitation has been successfully trialled in other medical disciplines such as stroke and cardiopulmonary care.

Trials have been conducted using wearable sensors which can be classified as either knee sensors which are inertial measurement units to specifically monitor the knee joint [14] or general physical activity sensors such as commercially available pedometers [15]. Technological interventions allow home-based telerehabilitation. This may provide the supervision needed for greater compliance and effectiveness, while also significantly reducing health resource use associated with face-to-face rehabilitation [16].

This narrative review explores the evidence for the use of wearable sensors in remote rehabilitation following knee arthroplasty surgery. It will discuss the reported effects on functional, clinical and sensor-related outcomes, patient-related outcomes and healthcare resource use. It will also summarise new developments and potential advances in this field.

Material and Methods

A pre-determined search strategy was used. MEDLINE/PubMed, Embase, CINAHL and Cochrane Database of Systematic Reviews were searched from 1st January 2000 to 17th February 2022 for potentially eligible studies. Search terms relating to arthroplasty surgery of the knee, wearable sensor technology and remote physiotherapy or telerehabilitation were utilised. The full form of this strategy is available in Fig. 1. Two authors (SK and ME) reviewed the results of this search, with the senior author (JP) providing input to arbitrate any disagreement. The PRISMA [17] flow diagram demonstrating the results of the review is shown in Fig. 2.

Studies were included in this narrative synthesis if their interventions included the use of wearable sensor technology in the outpatient setting following primary TKA or unicompartmental knee arthroplasty (UKA). Simultaneous or sequential bilateral knee surgery was included while revision TKA was excluded. Wearable sensor technology was defined as “the application of data-recording transducers onto a person’s body or clothing to monitor measurable health indicators” [18]. Active remote monitoring with the opportunity to guide rehabilitation was mandatory. Those who did not fulfil the inclusion criteria were excluded. Where applicable, standard care was defined as the usual care provided by the institution or in the trial protocol.

Wearable sensors used were categorised as one of two subtypes: knee sensors and physical activity (PA) sensors. Knee sensors are inertial measurement units (IMUs) applied at or around the knee and provide joint-specific data including the range of motion (ROM) and are gaining popularity. PA sensors typically record metrics including step counts and active and sedentary time and are often widely commercially available.

There is significant heterogeneity in the literature with respect to rehabilitative techniques, standard care, duration of follow-up and outcome measures. To reduce this heterogeneity, the studies were subdivided into either those where remote rehabilitation was provided as an additional intervention or those where it was used as an alternative intervention to the standard rehabilitative care provided by the authors’ institution(s).

Results

Fourteen studies were found eligible for inclusion. Five studies reported on the use of knee sensors (one cohort study, four randomised control trials [RCTs]) while nine studies reported on PA sensors (one cohort study, eight RCTs). Ten studies consisted of only participants following TKA. Three combined TKA and total hip arthroplasty (THA) participants and one combined TKA and UKA participants. Study characteristics are shown in Tables 1 and 2.

Knee Sensors

Additional Intervention

In a pilot RCT of 20 patients, standard care was eight weeks of in-person outpatient rehabilitation [19]. These were two to three sessions per week and supplemented with an unsupervised home exercise programme. Intervention care was additional remote supervision of the home exercise programme via *interACTION* wearable sensors. The original intention of the study was to encourage the intervention group to reduce their number of weekly physiotherapy visits but there was no significant decrease compared with controls. Remotely supervised rehabilitation was therefore an additional intervention. The authors found no significant

Fig. 1 Literature search strategy utilised

"knee joint" OR knee.ti,ab OR exp "KNEE JOINT"/ OR KNEE/) AND prosthe* OR arthoplast* OR replace*.ti,ab OR ARTHROPLASTY/ OR "ARTHROPLASTY, REPLACEMENT"/ OR "BONE-ANCHORED PROSTHESIS"/ OR "JOINT PROSTHESIS"/ OR "PROSTHESES AND IMPLANTS"/ OR "KNEE PROSTHESIS"/ OR "ARTHROPLASTY, REPLACEMENT, KNEE"/ OR TKR OR TKA OR UKA OR UKR OR "unicompartmental knee replacement" OR "partial knee replacement" OR "unicompartmental knee arthroplasty".ti,ab

AND

exergam* OR "digital patient engagement" OR "virtual reality" OR fitbit OR jawbone OR iwatch OR "activity track*" OR "step count*" OR "activity monitor*" OR "step monitor*" OR axivity OR tracpatch OR geneactiv OR activpal OR "samsung active" OR pedometer* OR actigraph* OR smartwatch* OR smartphone* OR "smart technolog*" OR acceleromet* OR gyroscop* OR "wearable device*" OR "wearable technolog*" OR "wearable sensor*" OR "wearable electronic device*" OR actigraph* OR "inertia* measurement unit*" OR "remote monitor*" OR telemonitor* OR sensewear OR SWA OR mhealth OR IDEEA OR rehagait OR "inertia* sensor*" OR neo-gait OR vicon OR kinematic* OR "kinematic wearable device*" OR e-ar OR mhealth OR REHub OR digiwalker* OR lifecorder* OR interaction OR VERA OR SWORD OR "fitness tracker" OR IMU OR BPMpathway.ti,ab OR EXERGAMING/ OR "VIRTUAL REALITY"/ OR "WEARABLE ELECTRONIC DEVICES"/ OR "FITNESS TRACKERS"/ OR ACTIGRAPHY/ OR ACCELEROMETRY/ OR exp "MONITORING, AMBULATORY"/ OR "BIOMECHANICAL PHENOMENA"/

AND

"enhanced recovery" OR "ERAS" OR "home-based recover" OR "postoperative rehabilitation" OR "postoperative recovery" OR physiotherap* OR "physical therap*" OR exercise OR "exercise therap*" OR "physical activit*" OR rehabilitat* OR telemedicine OR telerehabilit* OR "muscle stretch*" OR "physical functional performance".ti,ab OR "EXERCISE THERAPY"/ OR "PHYSICAL THERAPY MODALITIES"/ OR "EXERCISE MOVEMENT TECHNIQUES"/ OR "MUSCLE STRETCHING EXERCISES"/ OR exp EXERCISE/ OR TELEMEDICINE/ OR TELEREHABILITATION/ OR "PHYSICAL FUNCTIONAL PERFORMANCE"/ OR "PHYSICAL FITNESS"/

[DATE LIMIT: 2000-2022]

difference between the groups in terms of the Timed Up and Go (TUG) test, unilateral balance test, stair climb test or 6-min walk (6 MW) distance at 5- and 10-weeks post-TKA. There was also no difference in the change in the Activities of Daily Living Scale (ADLS) of the Knee Outcome Survey (KOOS), Numeric Pain Rating Scale (NPRS) or the Veterans RAND 12-Item Health Survey (VR-12). The results of this study must be considered in the context of their small numbers and relatively short follow-up period.

Ramkumar et al. conducted a cohort study where 22 patients were given a mobile application and a paired knee sleeve sensor from two to three weeks pre-operatively to three months post-operatively in addition to standard care [20]. It provided daily reminders to complete home exercises, transmitted continuous data during exercises and alerted the care team if 90 degrees of flexion was not achieved by two weeks post-operative. Mobility was back to baseline by 6 weeks and 30% better by three months. The mean KOOS improvement was 39.3 points. There was no control group for comparison.

Alternative Intervention

A larger study of 142 patients compared two weeks of face-to-face clinic-based rehabilitation with an alternative of one week of face-to-face followed by one week of remotely supervised rehabilitation with a wearable sensor [14]. At three-month follow-up, there was no significant difference in knee ROM, hamstring strength and visual analogue score (VAS) between the groups. Quadriceps strength was improved in the intervention group, while TUG test was better in the standard care group. An important limitation of this study was that patients who did not achieve 80 degrees of active knee flexion in the first five outpatient sessions were excluded from the study, so the efficacy of this method in the more challenging rehabilitation cases is undeterminable.

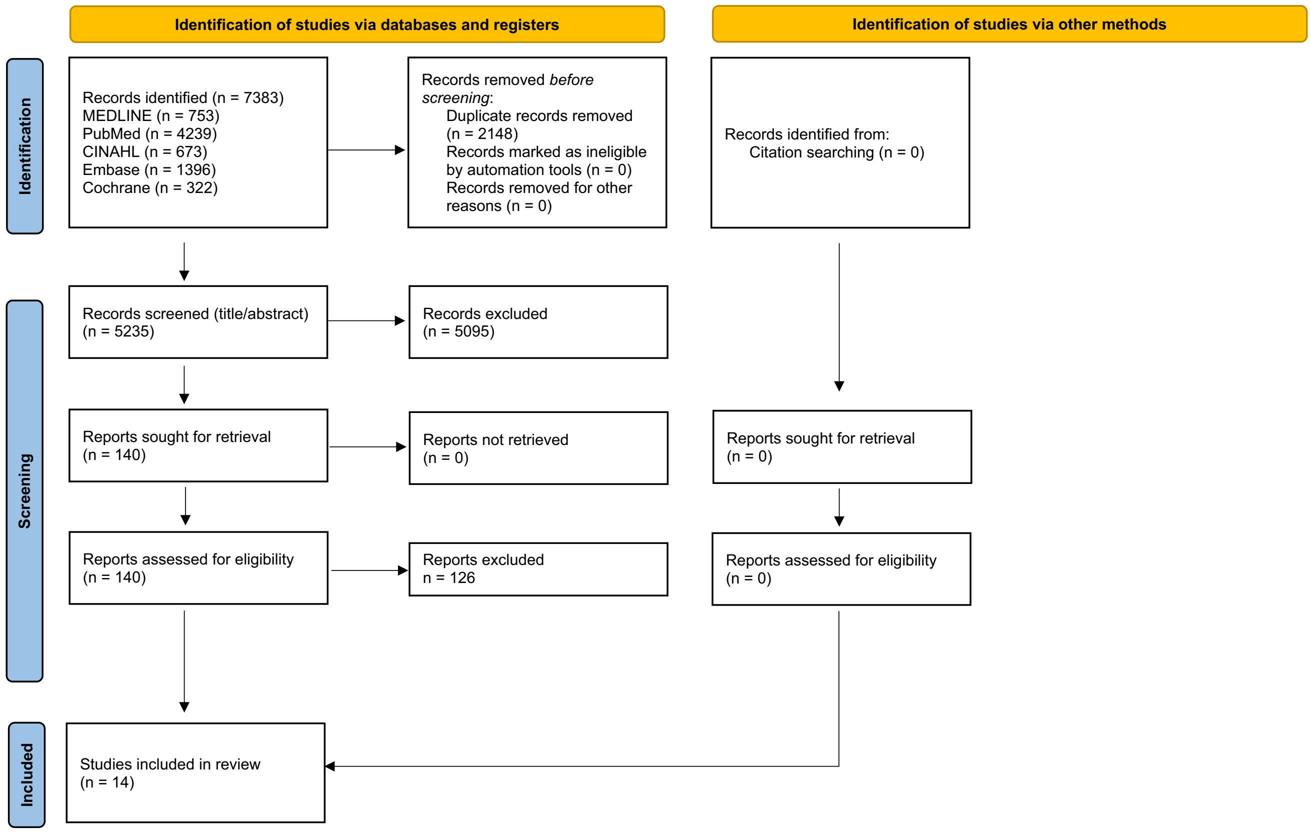

Fig. 2 PRISMA flow diagram demonstrating results of literature review

Two papers by Correia et al. report short- and longer-term results of the same study [16, 21]. Over an eight-week rehabilitative period, they compared domiciliary face-to-face rehabilitation with an alternative of remote monitoring using the SWORD digital biofeedback wearable sensor group system (SWORD Health, Porto, Portugal). The wearable sensor group showed superior TUG test and KOOS results at the final six-month follow-up. This group also had better knee ROM at early follow-up, but this converged to the level of the standard care group by six months.

Physical Activity Sensors

Additional Intervention

Christiansen et al. provided their intervention group with a commercially available activity monitor [22]. Participants received a daily step goal which was updated weekly in response to the remotely gathered data. Monthly phone calls were provided after discharge from physiotherapy. This was compared with standard care. The authors found a greater increase in step count and moderate to vigorous physical activities (MVPA) in the intervention group which persisted to 12 months, and further analysis demonstrated a greater decrease in sedentary time [23].

In their intervention group, Paxton et al. monitored PA using a wearable sensor and mobile application in patients after they had already received outpatient physiotherapy for six to eight weeks [24]. The intervention group had an additional 12 weeks of rehabilitation and included activity feedback, weekly goal setting and monthly support groups. This was in addition to the standard care provided to the control arm. No difference was found in step count, TUG test, 6 MW or gait speed.

Colomina et al. examined the effect of their intervention on health status, unplanned visits and admissions and cost-effectiveness in their RCT of 59 higher-risk patients following THA or TKA [15]. They compared standard care with the multidisciplinary team mHealth system with the aim of improving discharge destination and healthcare costs. The intervention group had a lower rate of unplanned hospital visits, and the intervention was found to be cost-effective. There was no difference in 12-item short-form survey (SF-12) scores or unplanned readmissions.

Another study also targeted patients at higher risk of increased resource use [25]. They selected patients undergoing THA or TKA with an intermediate risk of requiring

Table 1 Study characteristics for studies of knee-specific wearable sensors

Author, Year	Country	Participants	Age (years): Mean (SD)	Intervention	Intervention Care (IC) sample size	Standard Care (SC) sample size	Follow-up (weeks post-operative)	Study type	Additional or alternative intervention?	Results
Bell 2020	USA	TKA	64.4 (8.2)	8 weeks: Starting at 2–3 face-to-face sessions per week in clinic, target of 1 per week	10	10	5, 10	RCT	Additional	No significant difference in physiotherapy use, KOOS-ADL, VR-12, ROM, TUG, unilateral balance test, Stair Climb Test, 6-min walk IC: Improved NPRS at 10 weeks
Correia 2018, 2019	Portugal	TKA	68.5 (7.0)	8 weeks: Remotely monitored rehabilitation for. 5 × 30 min per week	30	29	13, 26	Pseudo-RCT	Alternative	IC: Superior TUG and all KOOS subscales at 6 months; knee ROM initially superior in but converged with SC by 6 months
Piqueras 2013	Spain	TKA	73.3 (6.5)	10 days of 1-h virtual reality sessions. 5 face-to-face supervision, 5 remotely supervised	68	65	3, 13	RCT	Alternative	Equivocal change in VAS and hamstring strength IC: Superior active extension at 3 weeks only; superior quadriceps strength at both end points SC: Superior TUG at 3 months
Ramkumar 2019	USA	TKA	64.3 (not available)	Three months: Daily reminders to do exercises	22	N/A	6, 13	Cohort	Additional	Mobility back to baseline by 6 weeks, 30% improvement by 3 months, KOOS improvement of 39.3. Exercise compliance 62%

Table 2 Study characteristics for studies of physical activity wearable sensors

Author, Year	Country	Participants	Age (years): Mean (SD)	Intervention	Intervention Care (IC) sample size	Standard Care (SC) sample size	Follow-up (weeks post-operative)	Study type	Additional or alternative intervention?	Results
Christiansen 2020	USA	TKA	67 (7.0)	6 months: Standard outpatient physiotherapy, Fitbit Zip (Fitbit, San Francisco, CA, USA), weekly steps/day goal from physiotherapist, monthly follow-up phone calls from research assistant	14	12	26, 52	RCT	Additional	IC: Higher step count and MVPA at 6 and 12 months. 60% adherence to monitoring own steps Adherence to intervention 45–60%
Coleman 2021	USA	TKA	67 (7.0)	6 months: Standard outpatient physiotherapy, Fitbit Zip, weekly steps/day goal from physiotherapist, monthly follow-up phone calls from research assistant	14	12	26, 52	RCT	Additional	IC: Greater reductions in sedentary time
Colomina 2021	Spain	THA, TKA	SC: 74 (8) IC: 72 (9)	90 days: Self-management app (automated feedback), communication with care team, Fitbit Flex 2 activity tracker, case manager for supervision	29	30	13, 26	RCT	Additional	No significant difference in SF-12 between groups IC: 50% fewer unplanned visits. Cost-effective (savings of $132.96 to $153.66 per patient)

Table 2 (continued)

Author, Year	Country	Participants	Age (years): Mean (SD)	Intervention	Intervention Care (IC) sample size	Standard Care (SC) sample size	Follow-up (weeks post-operative)	Study type	Additional or alternative intervention?	Results
Crawford 2021	USA	TKA, UKA	TKA: 64.5 (8.9) UKA: 62.6 (9.3)	mymobility app (Zimmer Biomet, Warsaw, IN, USA) and Apple watch (Cupertino, CA, USA), reminders to complete exercises, messaging capability. Default care was no in-person physiotherapy	208	244	4, 13	RCT	Alternative	No difference in ROM, SLS or TUG. No difference in MUA rate, urgent care attendance or readmissions SC: Better change in KOOS in controls., IC: Fewer ED visits. Fewer had one or more face-to-face physiotherapy visits
Lebleu 2019	Belgium	THA, TKA	62 (10)	13 weeks: Personalised and daily exercises with feedback via tablet	132	N/A	13	Cohort	Alternative	Pre-operative physical activity reached by seven weeks
Losina 2018	USA	TKA	65 (8)	Telephonic Healthcare Coaching (THC) or Financial Incentive (FI) or THC and FC in combination	113	37	26	RCT	Additional	THC + FI: greatest increase in PA and step count
Mehta 2020	USA	THA, TKA	66 (IQR: 58–73)[a]	2 weeks: All: Activity monitor with paired smart phone, pain score tracking, non-adherence messages. Subgroup of IC: Motivational messages with goal setting and gamification and message to support partner	54	124	2, 6	RCT	Additional	No difference in step count for subgroup receiving motivational messaging and goal setting. No difference in discharge destinations

Table 2 (continued)

Author, Year	Country	Participants	Age (years): Mean (SD)	Intervention	Intervention Care (IC) sample size	Standard Care (SC) sample size	Follow-up (weeks post-operative)	Study type	Additional or alternative intervention?	Results
Paxton 2018	USA	TKA	SC: 64 (6) IC: 63 (7)	12 weeks: Daily physical activity feedback programme, Fitbit, weekly call, modified goals, monthly face-to-face group support meetings	22	19	12	RCT	Additional	No difference in PA, TUG, 6 MW, or gait speed IC: 100% retention (completion of 12 weeks), 92% adherence (% days with PA collection), 65% dose goal attainment (% meeting weekly goals)
Tripuraneni 2021	USA	TKA	SC: 65.1 IC(A): 62.8 IC(B): 63.9	8 weeks: 2-week pre-operative and 6 weeks post-operative exercises. Monitored with exercise programme chosen by physician	153	184	4, 13, 26, 52	RCT	Alternative	SC: Higher KOOS-JR at 6 months No other difference in outcomes (MUA rate, EQ-5D, ROM)

[a]IQR used in summary statistics in the original paper

post-discharge facility care. The intervention group received a wearable activity tracker, post-operative goal messages and a connection with the clinical team as required, with a subgroup receiving gamification and social support. There was no difference in PA or discharge destination between subgroups, but the intervention arm had a lower rehospitalisation rate.

Various combinations of attention control, motivational interviews and financial incentives to patients for completing exercise logs were compared as interventions in a four-armed RCT by Losina et al [26]. Financial incentives consisted of an initial reward of $105 which was reduced or increased dependent on the completion of physical activity logs. They found a combination of both telephonic health coaching and financial incentives provided the greatest change in weekly physical activity at a six-month follow-up.

Alternative Intervention

Standard in-person rehabilitation was compared with an intervention of a smartwatch and smartphone application in a multicentre trial of 454 patients following TKA or UKA. By default, the intervention group was not assigned any in-person physiotherapy, but this could be arranged at the discretion of the care team and dependant on the results of the remote monitoring. Ninety-day follow-up found no difference between standard care and remote rehabilitation when assessed by ROM, single leg stand, TUG time, MUA rate or mean KOOS-JR (KOOS-Joint Replacement) score [27]. Fewer patients in the intervention group required in-person physiotherapy and had fewer emergency department visits. A similar study of TKA and THA patients compared standard face-to-face rehabilitation with remotely monitored rehabilitation using a PA sensor and a mobile application at 1-, 3-, 6- and 12-month follow-up [28]. It found no difference in change in ROM, MUA rate or EQ-5D-5L. Change in KOOS-JR was lower at some follow-up points but did not reach clinical significance.

A cohort study of 132 THA and TKA patients delivered remote rehabilitation monitored with a fitness tracker, daily goals and regular feedback [29]. Patients achieved pre-operative activity levels by the seventh week post-operative, with no change at three months. There was no control group for comparison.

Discussion

There is a growing interest in the use of technology to aid rehabilitation following knee replacement surgery [13, 18]. The literature includes several studies on the effects of remotely monitored outpatient rehabilitation using wearable sensors.

Most studies found similar outcomes when knee sensor remote rehabilitation was used as an alternative to face-to-face therapy, which is clearly more resource intensive [14, 27, 28]. One study reported superior outcomes compared to traditional outpatient therapy [21]. When used in addition to standard care, some studies found an improvement in physical activity, sedentary time and re-hospitalisation rates [15, 22, 23, 25, 26].

There were some significant limitations to the comparison of the studies. This was related to methodological heterogeneity. Some studies involved both THA and TKA [28, 29]. These patients have differing rehabilitative needs and sub-analyses of patients as separate groups were not always undertaken. The study of patient groups at higher risk of complications [15, 25] was of particular interest as these patients are often the source of higher postoperative costs, but this restricts comparison with the other studies. Follow-up periods also varied significantly; for some studies, this was less than three months [19, 25, 27] while others were up to 12 months [22, 23, 28]. Some of the studies were presented as pilot or feasibility studies due to their small cohort numbers, and so were too underpowered to draw robust conclusions [19, 22–24]. The definition of “standard care” was used pragmatically in this review and differed between studies due to the variation in rehabilitation between institutions. Some utilised unsupervised home exercises only, while others provided face-to-face physiotherapy in the institution or in patients’ homes.

Conclusion and Perspective

The use of remotely monitored rehabilitation with wearable sensors has the potential to provide the advantages of supervised rehabilitation with respect to compliance and assessment of complications. It may also reduce the costs of post-operative rehabilitation following arthroplasty surgery [10], which is known to be highly variable between individuals, institutions and healthcare systems [6, 7, 30].

An adequately powered and more rigorous RCT is needed with at least six months of follow-up reporting outcomes covering all relevant domains: measures of functional assessment, patient-related outcome scores, clinical outcomes and healthcare resource use. Future studies should attempt to correlate findings from wearable sensors with different pre-, intra- and post-operative variables to aid understanding about which variable is associated with better outcomes. For example, with the push for new techniques and technologies such as kinematic (functional or patient-specific) alignment, use of minimally invasive surgery, robotic-assisted or navigated TKA there needs to be robust evidence associated with the use of these technologies. Continuous data collection enables monitoring of temporal changes in a more meaningful way rather than simply using snapshot data when a patient visits the clinic at a certain time point. The use of Artificial Intelligence to diagnose and predict patients with poor or suboptimal outcomes will help reduce the further burden on healthcare, improve patient satisfaction and ensure timely rehabilitation in patients undergoing a total knee replacement.

Author contributions SWK: Manuscript conception, literature search and review, manuscript preparation and editing. ME: Literature review, manuscript preparation and editing. BHvD: Manuscript conception, preparation and editing. SJ: Manuscript conception, preparation and editing. JK: Literature search. HGP: Manuscript conception, preparation and editing. JP: Manuscript conception, literature review, preparation and editing.

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Data availability The data that support the findings of this study are available from the original research articles included in the references, and from the corresponding author [SK] upon request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical standard statement This article does not contain any studies with human or animal subjects performed by any of the authors.

Informed consent For this type of study, informed consent is not required.

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