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Feasibility Review of Wearable Kinematic Sensors in Post Knee Arthroplasty Patients

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Abstract

Introduction: Post-operative surveillance of joint range of motion after knee arthroplasty is a necessity. However, as the number of these surgeries increase, there has been a significantly increased burden to have sufficient follow up. In this light, the primary purpose of this study was to assess feasibility of novel wearable kinematic sensors in detecting patient mobility limitation compared to clinical and goniometer measurements in post knee arthroplasty patients. A secondary objective of the study was to identify gaps in goniometry used in typical current follow up protocol for this population.

Methods: Two separate searches were conducted to fulfill the two objectives of this study. The databases of Medline, PubMed and Cochrane library were searched using medical subject headings and keywords during August 2020. Titles and abstracts were screened based on specified inclusion criteria and then full text reviewed.

Results: The search for the feasibility of wearable kinematic sensors yielded seven studies after screening. The search for gaps in goniometry yielded five studies after screening and full text review.

Discussions: It was found that limitations with traditional goniometry involves user experience dependence, end digit preference and poor inter-rater reliability. Wearable sensors have the advantage over goniometry in the areas of objectivity, continuity, better supervised recovery and the measurement of multiple parameters in parallel. Current limitations with these sensors are the concerns with privacy regarding GPS data and loss of data. Furthermore, the requirement of recalibration and relative sensor drift are a significant issue. Measurement of the operated leg does not give a holistic picture of gait and sensors only on the forearm can only be used to measure daily activity. Future avenues with this technology include adjunct telerehabilitation, recording subjective in parallel to objective data and using multiple sensors on both lower limbs.

Conclusion: The study demonstrated that it is feasible and advantageous to utilize wearable kinematic sensors to monitor the post-operative period of knee arthroplasty patients.

Keywords: Wearable electronic devices; knee arthroplasty; mobility limitation, goniometer.

Introduction

Knee arthroplasty is one of the most common orthopedic procedures due to the high prevalence of knee cartilage pathologies such as osteoarthritis, rheumatoid arthritis and post-traumatic degenerative joint disease. In the year between 2017 and 2018, there were 54102 knee arthroplasties performed on patients who had a principal diagnosis of osteoarthritis and the incidence is steadily increasing [1]. Joint replacement remains as one of the most clinically successful and cost-effective treatments for severe osteoarthritis of the knee [2]. However, flexion contractures are a common deformity for these patients [3]. Limitations in post-operative joint mobility is established as a successful surrogate metric to predict the formation of flexion contractures. However, there remains a lack of tools to objectively measure activity and kinematic data to monitor patients in the post-operative period.

The current follow-up schedule is variable, but the typical protocol of post knee arthroplasty involves clinical

measures of mobility and range of movement (ROM) measurements. These are performed by a physiotherapist who uses tests such as the timed up-and-go (TUG) and a goniometer to measure ROM. Nevertheless, a significant number of patients prefer not to come into clinics if asymptomatic [4]. Over the last few years there have been innovations in novel wearable kinematic sensors. These devices can provide objective knee kinematic data such as activity level and ROM which can potentially bridge the gap in patient monitoring in asymptomatic patients. However, there has been a paucity of evidence on the feasibility of this technology.

The lack of uptake of wearable kinematic sensors is due to a few reasons. Given the novelty of this technology, there is a dearth of research in the area. There are many different sensor types available that measure different data. This technology typically consists of one or two sensors such as: accelerometer, gyroscope, barometer, magnetometer, thermometer or pedometer. Therefore, given the breadth of sensors available and the limited research on their feasibility in the post-operative period, the aim of this review is to help facilitate their use in clinical practice.

The primary objective for this review was to investigate the feasibility of wearable kinematic sensors in detecting patient mobility limitation compared to clinical and goniometer measurements in post knee arthroplasty patients. A secondary objective was to identify gaps with goniometry performed in the post-operative follow up period.

Methods

The online databases of Medline (Ovid), PubMed and Cochrane library were searched during August 2020 using Medical Subject Headings (MeSH) and keywords. Searches were limited to systematic reviews, meta-analyses, randomised control trials, clinical trials and cohort studies. No time limit was assigned given the limited literature in the area.

Two separate searches were conducted to fulfill the two different objectives of this review. The inclusion criteria for the first search involving the feasibility of wearable kinematic sensors in detecting patient mobility limitation were: must include wearable device, must include post-operative participants, assessing patient mobility and written in English. The inbuilt sensors in mobile phones were also considered a wearable device if they were kept on the participants person and physical activity was accepted as a measure of participant mobility. The inclusion criteria for the second search involving gaps with goniometry were: must have used a goniometer to measure ROM, must include post-operative participants and written in English.

Further, hand searching was conducted in the reference lists of manuscripts for additional studies. The full search history for the primary and secondary objectives are presented in (Tables 1 & 2) of the appendix. Studies were first screened on basis of title and abstract for inclusion criteria and the remaining studies were full text reviewed.

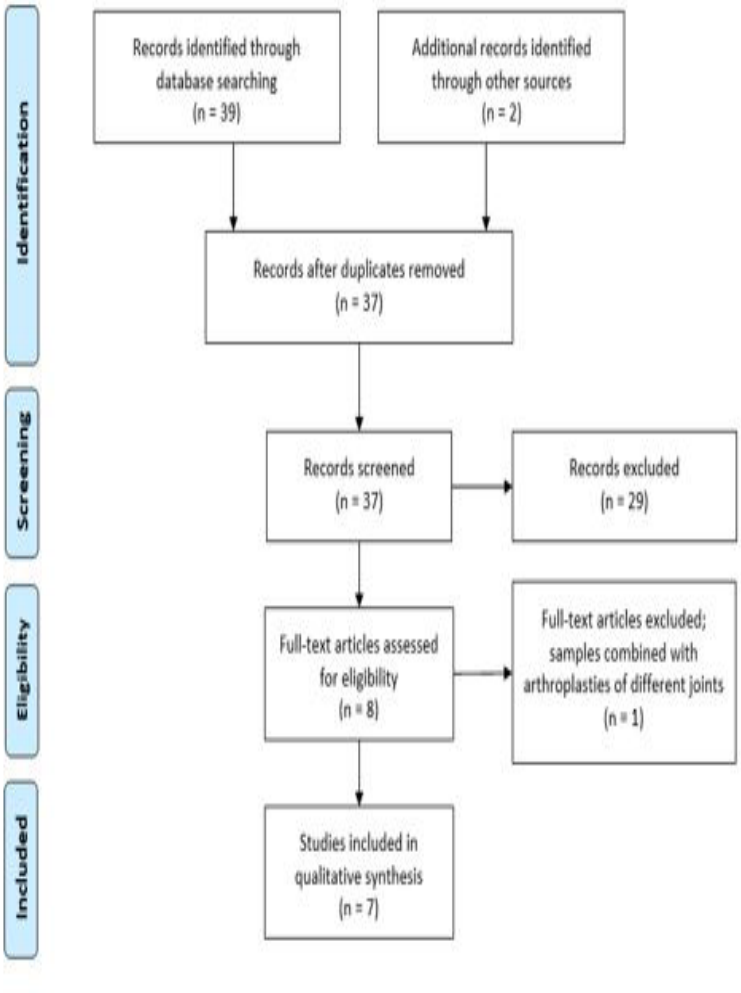

Figure 1: PRISMA flow diagram search for the feasibility of wearable sensors.

Results: (Figures 1 & 2)

A summary of the identified study's findings can be found in (Tables 3 & 4) of the appendix.

Discussion

Current follow up and monitoring of rehabilitation protocol

Table 1: Medline search history.

Line	Feasibility of wearable sensors entry	Gaps with goniometry entry
1	Arthroplasty, Replacement, Knee/	Arthroplasty, Replacement, Knee/
2	("Knee arthroplast*" or "Knee Replacement Arthroplast*" or "Total Knee Arthroplast*" or "Total Knee Replacement" or "Knee Arthroplast*" or "Unicompartmental Knee Arthroplast*" or "Unicondylar Knee Arthroplast*" or "Partial Knee Arthroplast*" or "Unicondylar Knee Replacement" or "Partial Knee Replacement" or "Unicompartmental Knee Replacement" or "Knee reconstruc*").tw.	("Knee arthroplast*" or "Knee Replacement Arthroplast*" or "Total Knee Arthroplast*" or "Total Knee Replacement" or "Knee Arthroplast*" or "Unicompartmental Knee Arthroplast*" or "Unicondylar Knee Arthroplast*" or "Partial Knee Arthroplast*" or "Unicondylar Knee Replacement" or "Partial Knee Replacement" or "Unicompartmental Knee Replacement" or "Knee reconstruc*").tw.
3	wearable electronic devices/ or fitness trackers/	Goniomet*.mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]
4	("Wearable Electronic Devic*" or "Kinematic sensor" or "Flexible wearable sensor" or "Wearable technology" or "Wearable sensor" or "Knee monitoring" or "Knee kinematics" or "Kinematic" or "Joint kinetics" or "Kinematic technology" or "Wearable computer" or "Accelerometer" or "Gyrometer").tw.	Physical Therapists/
5	Arthrometry, Articular/	("Physical Therapists" or "Physio" or "Physiotherapist*").tw.
6	("Timed up and go" or "TUG" or "Arthromet*" or "Range of motion*" or "Articular range of motion" or "Knee range of movement" or "Passive range of movement" or "Active range of movement").tw.	14 or 15
7	Mobility Limitation/	17 or 18
8	("Mobility" or "Patient mobility" or "Ambulation Difficulty" or "Ambulation Difficulties" or "Difficulty Ambulation" or "Ambulatory Difficulty" or "Ambulatory Difficulties" or "Difficulty Walking" or "rehabil*" or "Recovery of Function*" or "Postoperative Complication*").tw.	16 and 19 and 20
9	1 or 2	
10	3 or 4	
11	5 or 6	
12	7 or 8	
13	9 and 10 and 11 and 12	

Table 2: PubMed and Cochrane library search history.

	Feasibility of wearable sensors entry	Gaps with goniometry entry
Input	("Knee arthroplast*" OR "Knee Replacement Arthroplast*" OR "Total Knee Arthroplast*" OR "Total Knee Replacement" OR "Knee Arthroplast*" OR "Unicompartmental Knee Arthroplast*" OR "Unicondylar Knee Arthroplast*" OR "Partial Knee Arthroplast*" OR "Unicondylar Knee Replacement" OR "Partial Knee Replacement" OR "Unicompartmental Knee Replacement" OR "Knee reconstruc*") AND ("Wearable Electronic Devic*" OR "Kinematic sensor" OR "Flexible wearable sensor" OR "Wearable technology" OR "Wearable sensor" OR "Knee monitoring" OR "Knee kinematics" OR "Kinematic" OR "Joint kinetics" OR "Kinematic technology" OR "Wearable computer" OR "Accelerometer" OR "Gyrometer" OR "Knee sensor*") AND ("Timed up and go" OR "TUG" OR "Arthromet*" OR "Range of motion*" OR "Articular range of motion" OR "Knee range of movement" OR "Passive range of movement" OR "Active range of movement" OR "Goniometer") AND ("Mobility" OR "Patient mobility" OR "Ambulation Difficulty" OR "Ambulation Difficulties" OR "Difficulty Ambulation" OR "Ambulatory Difficulty" OR "Ambulatory Difficulties" OR "Difficulty Walking" OR "rehabil*")	("Knee arthroplast*" OR "Knee Replacement Arthroplast*" OR "Total Knee Arthroplast*" OR "Total Knee Replacement" OR "Knee Arthroplast*" OR "Unicompartmental Knee Arthroplast*" OR "Unicondylar Knee Arthroplast*" OR "Partial Knee Arthroplast*" OR "Unicondylar Knee Replacement" OR "Partial Knee Replacement" OR "Unicompartmental Knee Replacement" OR "Knee reconstruc*") AND ("Goniomet*") AND ("Physical Therapists" OR "Physio" OR "Physiotherapist*")

Table 3: summary of findings of studies involving wearable kinematic sensors in post knee arthroplasty patients.

Reference	Publication year	Research question	Findings	Study design	Strengths	Weaknesses
Huang et al.(20)	2020	Do novel wearable sensor-based systems perform knee range of movement measurements as well as the gold standard Cybex isokinetic dynamometer (or Cybex) professional rehabilitation equipment?	Experimental results verified that the proposed wearable system is effective and comparable with the established range of motion measurement instruments.	Non-randomised control trial	Participants were homogenous at baseline (tables provided with participant demographics). Appropriate control group utilised Cybex isokinetic dynamometer, the current gold standard.	Small sample size (n=35). Sample was selected from a single hospital. Very little detail on the how the participants were sorted into treatment and control groups.
Ramkumar et al.(18)	2019	How valid and feasible is a remote patient monitoring (RPM) system in terms of the frequency of data interruptions and patient acceptance?	RPM provided a continuous stream of previously immeasurable data without any loss, portraying a more accurate picture of the patient's recovery after TKA. All participants recommended the platform to others and f ound it to be "engaging," "motivating," and easy to use.	Pilot cohort study	Strict inclusion criteria mean that population of interest is well represented. Exclusion criteria prevent potential confounders that may decrease rehabilitation ability.	Small sample size (n=25). Possible Hawthorne effect due to patient monitoring. Risk of selection bias as a significant proportion of Americans do not presently own a smartphone and are unable to use the platform. Furthermore, participants are selected from the population of a single hospital.

Kline et al.(16)	2019	Could a telehealth-based intervention monitored with fitness trackers improve physical activity and functional outcomes after total knee replacement?	Initial evidence is promising for the potential of telehealth to reduce rehabilitation costs after total knee arthroplasty.	Rand omised control trial protocol	Assessors were blinded. Appropriate 2-arm and parallel study design. A computer-generated randomization codes was generated stratified by decade of age and presurgical physical activity. Randomisation done by investigator not participating as an interventionalist or assessor to allow group allocation concealment. Strong exclusion criteria to prevent confounders. Sample size selection based on statistical power analysis of pilot study and accounts for a 20% drop out rate.	No blinding possible of participants or interventionalists. Only US military veterans selected means that more males were recruited. Intervention only available to people that own a smartphone and internet connection to connect to fitness tracker that may introduce selection bias. Large age range (50 to 85 years of age). Though baselines are stated to be taken, they have not been summarized in a table.
Losina et al.(17)	2018	Do financial incentives and health coaching improve physical activity in persons undergoing TKR?	A dual telephonic health coaching and financial incentives intervention led to substantial improvements in step count and physical activity following TKR.	Rand omised control trial	Adequate randomisation was implemented in block sizes of 4 and was stratified by age (<65 vs. ≥65 years). Participants were discontinued if they underwent a surgery requiring overnight hospitalization as this confounds patient activity.	Only 150 of 202 recruited participants provided both preoperative and postoperative activity data. No blinding is possible in this type of study.
Harm elink et al.(24)	2017	What is the additive effect of a digital activity coaching system being introduced alongside a home-based exercise program after a total knee arthroplasty on physical functioning measured with the TUG after two weeks, six weeks and three months?	A two-week home-based exercise program monitored by clinical and accelerometer data is particularly appropriate for patients with a reasonably good prognosis for recovery after total knee arthroplasty).	Rando mised control trial	Large sample size (n=110) with power analysis conducted to ensure adequate power. Equal number of participants in control and treatment group. Appropriate block randomisation generated by a computer. Clinical and objective measurements measured (TUG and accelerometer). Appropriate inclusion criteria (adequate preoperative physical status, absence of compensatory movements, body mass index < 30).	Single blind only (though hard to conduct double blind given the nature of the intervention). Excluding obese (BMI >30) may introduce selection bias as much of the population with knee osteoarthritis are obese people. Intervention only available to people that own a smartphone and internet connection that may introduce selection bias. Baseline measurements taken though were not compared in the manuscript, therefore, unable to determine homogeneity of participants.

Chiang et al.(19)	2017	Are wearable sensors for monitoring knee range of movement after total knee arthroplasty an adequate alternative to track rehabilitation than traditional goniometer measurements?	The proposed wearable sensor approach can provide an alternative for continuous monitoring and objective assessment of knee ROM recovery progress for TKA patients compared to the traditional goniometer measurements	Pre- and post-interventional trial	-	Methodology was not documented in the manuscript but was referenced in a previous article by the same authors. Small sample size (n=18).
Calliess et al.(21)	2014	Are mobile gait analysis sensors able to measure specific knee parameters and gait information in patients undergoing total knee arthroplasty?	The introduced system appears to be suitable for outcome measurement after knee arthroplasty and has the potential to overcome some of the limitations of stationary gait labs while gathering additional meaningful parameters regarding the force limits of the knee.	Pre- and post-interventional trial	Inclusion criteria were strong and relevant to prevent confounders.	Small sample size (n=6). No baseline demographic data given. Includes only young and active patients and not representative of the population who require total knee arthroplasty

Table 4: Summary of studies involving goniometry in post-arthroplasty patients.

Reference	Publication year	Research question	Findings	Study design	Strengths	Weaknesses
Svensson et al.(13)	2019	What is the reliability of digital goniometers for measuring knee joint angles, considering intra-rater and inter-rater reliability? Are there any differences in the intra-rater reliability between a novice and an experienced assessor?	Digital goniometry showed very good intra-rater and inter-rater reliability.	Reliability study	Both assessors were blinded for their own and each other's measurements. To minimize the risk of systematic errors, the two assessors took turns to start measuring. The study was designed according to Guidelines for reporting Reliability and Agreement Studies.	There were calibration issues with the digital goniometer during the study. No comparison to gold standard measurements of X-ray. Study was not done on total knee arthroplasty patients exclusively.
Kornuijt et al.(6)	2019	How does knee flexion and extension progress in the first 8 weeks after primary total knee arthroplasty? What are the knee flexion and extension recovery patterns between patients with normal and delayed ROM recovery 8 weeks after total knee arthroplasty?	Both knee flexion and extension recover in a nonlinear manner after total knee arthroplasty. Poor postoperative knee function can be detected early, using ROM data from the first postoperative day up to the fourth week.	Prospective clinical trial	ROM movement measurements were standardised as physical therapist were given a written protocol on how to perform these measurements. Large sample size (n=137).	Both surgeon and physiotherapists measured knee ROM, possibly compromising the accuracy due to inter-rater reliability.
Stratford et al.(7)	2013	Does end-digit preference exist in the measurement of knee ROM in people after knee replacement?	The data showed strong end-digit preferences for 0s and 5s ($p<0.001$)	Reliability study	No attempt was made to standardise the measurement protocol across raters as this may influence their end digit preferences. No training on using goniometers was given therefore more likely to reflect day to day accuracy in the clinic.	Only 2 physiotherapists and 1 physiotherapist assistant were performing measurements. Unclear if physiotherapists and physiotherapist assistant were blinded to outcome of interest. This may lead to confirmation bias.

Jakobsen et al.(10)	2010	What is the intra-tester and inter-tester reliability of knee joint ROM and circumference measurements in patients with TKA?	There is relative intra-tester and inter-tester reliability of knee joint circumference was high, but the absolute reliability suggests that the circumferential and ROM measurement should be performed by the same physiotherapist.	Relia bility study	Patients were rested for 15min before being tested by the other assessor to prevent repetitive knee joint measurements from increasing knee joint ROM. Study looked at both novice and experienced assessors to better reflect the physiotherapist population. The testers were blinded to the identity of the patients by a curtain hanging down over the upper pelvis leaving only the legs and lower pelvis visible. Room temperature was controlled to prevent deviations in ROM from temperature fluctuations.	Both assessors were given standardized training prior to the study. Therefore, less likely to represent the wider population of physiotherapists. Only 2 assessors utilised.
Lenssen et al.(12)	2007	What is the inter-observer reproducibility (in terms of reliability and agreement) of active and passive measurements of knee ROM using a long arm goniometer, performed by trained physical therapists in a clinical setting in total knee arthroplasty patients, within the first four days after surgery?	Inter-observer agreement for flexion as well as extension was only fair. Reliability was found to be acceptable for comparison on group level, but poor for individual comparisons over time.	Reli ability study	Randomisation of patients was preformed to prevent the occurrence of systematic differences between observers because of repeated testing. Assessors measured ROM independently of each other. Good exclusion criteria to avoid confounders of ROM (Patients with a history of neuromuscular pathologies and patients with revision TKA were excluded).	Only 2 assessors from the same physiotherapist practice were utilised. No standardisation of the amount of force used for measurement of passive ROM.

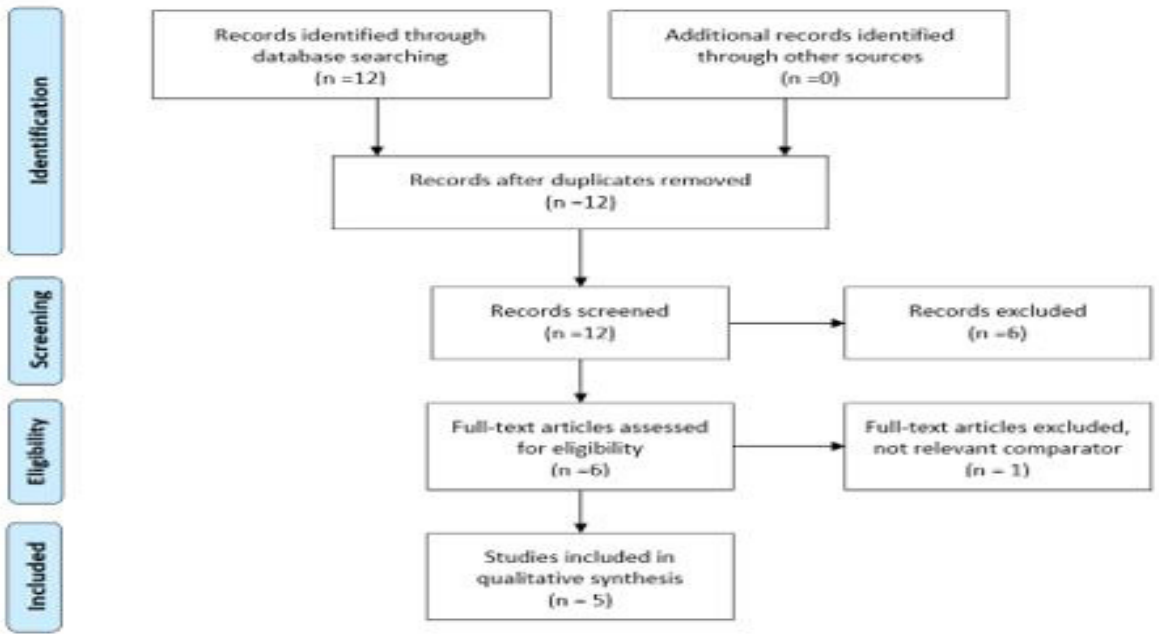

Figure 2: PRISMA flow diagram search for gaps with goniometry.

In the post-operative period after discharge from hospital, there is high variability on the follow-up and rehabilitation protocol. There is no apparent consensus on the ideal frequency, duration or intensity of the rehabilitation protocols which are hospital and surgeon specific [5]. The typical follow-up period involves a wound review by a nurse, physiotherapist or surgeon within two weeks following the surgery. The next time the patient will see the surgeon is at six to eight weeks after the surgery with or without weight bearing radiographs of the knee. During these sessions it is likely the physiotherapist will perform ROM measurements of both knees using a goniometer and some conduct clinical measures of mobility such as the TUG.

This typical follow-up protocol only allows two points in time where the patient can interact with medical staff over a 6–8-week period. Following this point in time, follow-up is highly variable. With many of the possible post-operative complications arising in this period, there is a necessity to be able to continuously monitor patients to avoid preventable complications.

Goniometry

Goniometric measurements are one of the kinetic metrics used to monitor rehabilitation in knee arthroplasty patients. It uses a goniometer to measure ROM at the fulcrum of a particular joint. ROM of a joint is an important proxy for overall joint function. The study by Kornuijt et al [6] found that low ROM measurements taken from the first operative day up to the fourth week can predict poor knee function. Though, goniometry requires an experienced user and the patient to attend the practice for measurements to be taken.

Access to services related to rehabilitation can be a problem to those who live outside metropolitan areas. Furthermore, travel times to practices may also inhibit patients from attending their specified outpatient appointments. This is especially the case when patients rather not attend their designated appointments when asymptomatic [4]. Though, it brings into question the reliability of a patient to assess their own mobility after surgery. Patients are not trained to look for possible complications in the rehabilitation period. Therefore, it is important that kinematic data can be obtained without the requirement of the patient attending outpatient appointments. This represents a weakness with the current follow-up protocol.

Limitations in the post-operative period involves ROM measurements that are prone to biases. Subjectivity in relation to goniometry involves the preference for specific end-digits. The study by Stratford et al [7] demonstrated that the physiotherapists of varying experience had a strong end-digit preference of 0 and 5. This notion has the capacity to compromise the validity of clinical decisions; for example, if a patient has improved ROM from their last visit. There have been many studies looking at goniometer reliability which have found that inter-rater reliability is generally worse than intra-rater reliability [8-12]. Though there have been improvements in reliability with the introduction of digital goniometers [13]. they still depend on an experienced user to take the measurements.

With the limited outpatient appointments these patients receive, it is more difficult to see trends of decline or improvement. With the existing follow-up protocol, the patient will get two instantaneous measurements over a 6–8-week period. With only two points for reference, the latest measurement can only be compared to one other point 4-6 weeks earlier. Given the lack of ability to obtain trend data, it makes it harder to make the clinical decision if a patient's mobility is truly improving, declining or plateauing.

To follow up post-operative patients requires experienced staff and sometimes the surgeon to perform goniometric measurements. This increases the staff burden and resources that could be used elsewhere in the patients' rehabilitation. Long term surveillance of joint mobility after knee arthroplasty is a necessity but as the number of these surgeries steadily increase, it has also become increasingly burdensome to have adequate follow-up [14].

Wearable Kinematic Sensors

Sensors to monitor organ health that can transmit data wirelessly to a doctor or care team has already become the norm and well established in other areas of medicine. For example, real-time arrythmia detection in cardiovascular patients that can wirelessly transmit data to their cardiologist [15]. With the introduction of novel wearable sensors, with the specific purpose of monitoring kinematic data, offers the opportunity for utilisation by orthopedic surgeons or physiotherapists.

There is a large breadth of wearable sensor types that measure different kinematic parameters. On the simpler side of the spectrum, a study developed a smartphone app to monitor physical activity as a surrogate for improvements in knee function [16]. With growing public interest in fitness tracking, many commercial activity trackers have also become available. One of these commercial sensors, Fitbit (San Francisco, USA), was utilised by Losina et al [17] and Kline et al [16] to track physical activity. Duration and

intensity of physical activity, tracked by steps taken, was used by these authors to substitute traditional clinical measures such as the TUG. The disadvantage of commercial sensors is that authors are not able to access algorithms used to calculate kinematic metrics. Furthermore, there have been developments in more complex wearable sensors that are attached to the lower limb. Ramkumar et al [18] investigated the use of a wearable knee sleeve. The device has the ability to continuously measure steps and ROM which requires pairing via Bluetooth to a smartphone. By contrast, alternate approaches have been taken by both Chiang et al [19] and Huang et al [20] who attached a sensor above and below the knee to obtain the angle between the fulcrum. By comparison, Calliess et al [21] utilised a sacral sensor in addition to two lower limb sensors.

Wearable sensors have multitudes of benefits over goniometric measurements in the post-operative period. The proposed sensors do not have the same subjectivity of end-digit preference and inter-rater reliability issues inherent to standard goniometry. Additionally, the information obtained from these sensors are objective kinematic data. Furthermore, it is possible that simple metrics such as step taken per day can be viewed by the patient themselves. This has the potential to motivate and engage patients to adhere to rehabilitation programs via the Hawthorne effect. This effect refers to when patients alter their behavior when they are aware, they are being observed [22] therefore, aiding in rehabilitation in the crucial eight weeks following a surgery.

The wearable sensors also offer the opportunity for surgeons and physiotherapists for a better supervised recovery of their patients. With typically only two follow-up appointments in the first eight weeks following surgery, most of the post-operative recovery occurs out of sight of the care teams [18] With the technology that enables continuous measurements of kinematic data, the supervision of recovery is no longer spatiotemporally constrained [20]. This allows trends to be observed beyond the typical two points in time that traditional goniometry offers. Furthermore, the data has the potential to monitor patient adherence and problems in their prescribed rehabilitation programs. As more instances in the patient's recovery can be tracked, it is more likely that limitations in mobility can be detected than traditional goniometry.

Often, there can be multiple factors in the development of non-favorable post-operative complications of knee arthroplasty. Unfavorable outcomes in mobility and joint function may be related to the surgery itself or patient therapy non-adherence. The proposed technology gives surgeons and physiotherapists the ability to identify the potential causes of adverse outcomes despite a well-executed recovery plan and expectation management [18].

Wearable sensors are capable of measuring multiple parameters in parallel. This allows the surgeon to improve patient evaluation with no additional effort [18] Furthermore, the surgeon would be able to receive a variety of metrics such as joint specific ROM and physical activity for a more holistic picture of joint and mobility limitation of the patient. Since kinematic measurements can be taken continuously and in parallel, less staff need to be trained and allocated to obtaining this data in the surgeon's clinic. This leads to saving both the patient's and surgeon's time by decompressing the clinic [18] In this light, the wearable technology presents the opportunity for reductions in human labor and financial savings.

While there are many benefits in using these novel wearable sensors, there are limitations and issues with the current technology. Commercial and some of the sensors mentioned in this review must communicate with a smartphone to be able to accurately calculate physical activity. As the patient's location is tracked via GPS, there is the potential for breaches in patient privacy. Furthermore, as the data is initially stored on the patient's smartphone, it is possible for data to be lost. There must be systems in place for frequent and reliable synchronisation to prevent data loss such as storing in the cloud. There are also concerns with data loss with the battery life of the sensors if they are unable to transfer data before losing power.

An inherent weakness for wearable sensors is the requirement for calibration of the equipment. The system used by Chiang et al [19] could be self-calibrated by the patient to confirm the accuracy of the data obtained by the sensors. Though, this method of calibration may not be ideal for all patients as some may need assistance from medical professionals. The frequency of calibration needed depends on the method the sensors are attached to the body. Sensor drift was a significant issue for Huang et al [20] and Chiang et al [19] who used Velcro and elastic belts. By contrast, Callies et al [21] utilised therapeutic tape to secure the sensors on the patient to prevent any significant relative motion between the sensors, thus, affecting data accuracy. This guarantees stable and defined sensor position. However, securing the sensors with tape means that the patient must continuously wear the sensors as taking them off would require further re-calibration. There are also issues on when to charge the devices, particularly with the commercial sensors which typically require charging every 3-4 days. It would be ideal to charge the devices at

night when the patients are sleeping, although, this would require re-calibration when remounted.

All the proposed sensors in the reviewed studies utilize only one limb to gather data. The sensors are not able to differentiate between the knee that was operated on and the knee that was not. In this light, no data can be obtained and no inferences can be made about the non-operated side [21]. By contrast, in the studies that utilised the commercial sensors, the device was mounted on the patient's forearm [16, 17]. In this approach, the forearm's movements act as a proxy for the patient's physical activity and overall joint function. However, it must be mounted on the user's non-dominant hand to minimize the amount of upper-limb motion independent of the lower limbs. Even so, it is not the perfect substitute metric as movements of the upper limb differ greatly to the lower limb.

The wearable sensors wirelessly transmit the obtained data for storage. This is commonly to a smartphone device. The Mobile Consumer Survey 2019 found that 11% of Australians do not own a smartphone device [23] Given this notion, it is likely that those of lower socioeconomic status would not be able to access this platform. This is especially the case if they have travelled from rural areas to receive treatment which have limited internet access. Therefore, there is the possibility to worsen firmly established health disparities [18]

Further Research and Future Prospects

Recommendations for future avenues with this technology involves the use of continuous kinematic measurements in conjunction with telehealth rehabilitation programs. With the ability to monitor a patient's recovery from a distance, patients now have the opportunity to participate in their rehabilitation programs from their homes. This is especially valuable when access to healthcare is limited by distance. This was the objective of Kline et al [16] who aimed to improve physical activity through adjunct telerehabilitation and address the gap in conventional rehabilitation. Furthermore, Losina et al [17] examined the feasibility of telephonic health coaching where physiotherapists have the ability to coach patients via video call. By contrast, Harmelink et al [24] investigated the additive effect of a digital activity coaching system introduced alongside a home-based exercise program to remove the requirement of intervention by medical staff in a patient led rehabilitation.

As many of these wearable sensors communicate with the patient's smartphone, it is possible that other subjective data could be monitored in parallel with kinematic data. Through the development of smartphone applications, a patient can log subjective parameters to their surgeon or treating team such as pain related parameters. Development of such applications might also involve an inbuilt telerehabilitation function so patients can access all their needs from a single platform. Gathering a broad range of objective and subjective data can add to a more holistic and detailed understanding of the patient's recovery.

In the field of multiple sclerosis, there has been the introduction of similar wearable technology. These inertial sensors are mounted on both lower limbs and the lower back therefore able to measure kinematic data from both legs [25] Given the increased number of sensors utilized, more parameters are able to be monitored for better gait analysis. Furthermore, these sensors are integrated into adhesive thus able to be mounted directly on the skin. This alleviates the common issue of relative sensor drift of elastic band mounted sensors used in the reviewed studies.

Conclusion

This review demonstrated that the recent development of wearable kinematic sensors is a feasible alternative to classical goniometric measurements and clinical measures of mobility obtained by physiotherapists. A review of all the latest research has yielded there are gaps with classical goniometry in the post-operative period such as end-digit preference and user experience dependency. The research suggests that the breadth of both objective and subjective parameters that can be gathered through wearable sensors eclipses the amount of data that can be obtained in the current follow up protocol. Despite this, there are significant issues with the current technology such as the need for frequent recalibration and relative sensor motion. This represents the necessity of further investigating approaches to counteract these limitations. The studies examined in this review demonstrate the large scope of novel sensors available, therefore, more research must also be conducted on individual sensors.

Conflict of Interest Statement

Each author certifies that they have no commercial associations (e.g., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted article.

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