

Variables for Daily Monitoring of Knee Osteoarthritis Symptoms: A Scoping Review

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Submitted to: Journal of Medical Internet Research
on: September 17, 2025

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Table of Contents

Original Manuscript.....	4
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Abstract

Background: Knee osteoarthritis (knee OA) is a multifactorial degenerative joint condition characterized by chronic pain, stiffness, and reduced mobility. Traditional clinical assessments are unable to capture the dynamic nature of symptom fluctuation in real-world settings, which limits timely and personalized intervention.

Objective: This scoping review aims to synthesize current research on sensor technologies and their associated data modalities used for daily life monitoring of knee OA symptoms. The review focuses on determining what types of physiological, biomechanical, and subjective signals can be used for daily symptom tracking.

Methods: A systematic literature search was conducted across PubMed, Web of Science, and IEEE Xplore following PRISMA-ScR guidelines. Eligibility criteria included non-invasive, sensor-based monitoring approaches that could be applied by patients in everyday environments. Extracted data encompassed sensor modalities, placement, measured variables, symptom types, and main study findings.

Results: A total of 18 studies were included, employing a variety of wearable and ambient sensor modalities, such as inertial measurement units (IMUs), electromyography (EMG), temperature and heart rate sensors, and mobile apps. Biomechanical parameters—such as range of motion, joint torque, and gait dynamics—were the most frequently monitored. However, the review also highlighted that there was a lack of integration between the collected sensor data and actionable feedback or adaptive monitoring frameworks.

Conclusions: The review suggests that while many sensor systems can technically measure relevant biomechanical and physiological markers, few of them are integrated into frameworks that enable patient feedback. The results underscore the importance of moving towards multidimensional monitoring approaches in daily life.

(JMIR Preprints 17/09/2025:84262)

DOI: <https://doi.org/10.2196/preprints.84262>

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Original Manuscript

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Conclusions: The review suggests that while many sensor systems can technically measure relevant biomechanical and physiological markers, few of them are integrated into frameworks that enable patient feedback. The results underscore the importance of moving towards multidimensional monitoring approaches in daily life.

Keywords: Knee osteoarthritis; symptom monitoring; wearable sensors; real-world data; biomechanical assessment; physiological variables; patient-reported outcomes; sensor integration; digital health; personalized medicine.

Introduction

Knee osteoarthritis (knee OA) is a degenerative joint disease characterized by the progressive loss of articular cartilage, subchondral bone remodeling, synovial inflammation, and the formation of osteophytes, ultimately leading to joint pain, stiffness, and functional limitations [1]. Knee OA primarily affects older adults, with a global prevalence estimated at 10–15% among individuals over 60 years of age[32]. In addition to aging, the increasing prevalence of obesity—a recognized major risk factor for knee OA—further contributes to the growing disease burden[33]. Knee OA is also frequently accompanied by other chronic conditions, such as cardiovascular disease, diabetes, and depression, which can influence symptom severity and complicate treatment approaches[34]. Together, these factors significantly impact patients' mobility, including walking ability and activities of daily living, daily functioning, and overall quality of life, posing a substantial burden on healthcare systems globally. Timely interventions can help manage pain, delay disease progression, and

maintain individual independence[2].

Traditional clinical assessments of knee OA rely on patients' periodic visits to healthcare providers[3], during which symptom severity is evaluated through physical examinations and self-reported questionnaires, while structural joint changes are assessed using imaging techniques such as X-rays or MRIs[4]. However, these assessment measures are limited in capturing the daily variability of knee OA symptoms. Such variability can be influenced by multiple factors, including physical activity levels[5], sleep quality[6], and environmental conditions[7]. Understanding the patterns of daily symptom fluctuations is crucial, as it can provide insights into individual triggers and coping mechanisms, enabling more timely and tailored interventions. Recent advancements in wearable sensors have enabled the collection and processing of various physiological and biomechanical data outside of clinical settings.

Previous reviews have examined general technological interventions for knee OA management [43,44], although few have specifically focused on continuous or daily symptom monitoring outside of clinical settings[38,39]. Moreover, existing reviews often emphasize either clinical outcome measures or technological feasibility[40,41,42], without systematically identifying the physiological, biomechanical, and other objective variables that could capture daily symptom variability. Addressing this knowledge gap is critical for informing the development of personalized, daily monitoring systems for knee OA, to better support early detection and improve patient outcomes.

This scoping review aims to synthesize current research on sensor technologies and the types of data they produce, referred to as data modalities, for the daily life monitoring of knee OA symptoms. More specifically: we explore what types of physiological, biomechanical, or other objective and subjective variables can be used to monitor knee OA symptoms?

Method

A scoping review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines [36]. The PRISMA-ScR checklist is provided in Appendix Table 2. Given the exploratory nature and descriptive aim of this scoping review, a single-reviewer screening approach (conducted by BC) was applied. This method was deemed appropriate due to the clearly defined inclusion criteria and the non-quantitative synthesis objective. To minimize selection bias, the screening process followed a structured and standardized protocol, and any uncertainties regarding inclusion were discussed among the authors.

Search strategy

The searched electronic databases included PubMed, Web of Science, and IEEE Xplore. These databases were chosen due to their extensive coverage of biomedical and technology-related literature. The search included a combination of Medical Subject Headings (MeSH) terms and free text keywords related to "Knee Osteoarthritis", "symptoms" and "noninvasive monitoring". The search strategy is reported in Appendix 7 and

was adapted for the specific requirements of each database. Our search results were uploaded into Endnote software for de-duplication and review.

Definition of Daily Life Monitoring Feasibility

To assess the applicability of monitoring tools for daily use, we predefined a set of criteria for feasibility. A monitoring modality was considered suitable for daily symptom monitoring if it met the following conditions:

- **Non-invasiveness:** The method is non-invasive, i.e. without any surgical or invasive access.
- **Portability and wearability:** The device or system must be capable of being used at home or in free-living conditions, without reliance on infrastructure of the hospital or clinic.
- **Use of technology without daily support:** The system must allow for data acquisition without the involvement of healthcare professionals in the daily environment of the patient.
- **Ecological integration:** The monitoring should occur without major interference with daily life activities (e.g., walking, sleeping) of the patient.

These definitions were applied during the eligibility screening process to evaluate whether the monitoring tools described in each study were compatible with daily symptom monitoring. Only studies meeting all criteria were considered eligible for inclusion.

Eligibility criteria

Each article was assessed for eligibility and inclusion by one reviewer (BC). Initially, the titles and abstracts were screened to assess their relevance to the objective and the study's inclusion criteria ([Textbox1]). Papers that met the inclusion criteria based on their abstracts were then subjected to a full-text review.

Textbox 1. Include and exclude criteria

Studies were included if they met the following conditions:

- Original quantitative or qualitative studies performed with individuals with knee OA, where symptoms such as pain, stiffness, swelling, or limited mobility were explicitly assessed;
- The study employed non-invasive, sensor-based methods with the intent to monitor one or more knee OA symptoms;
- The sensor modality and monitoring approach demonstrated feasibility for daily, unsupervised use based on the operational definition above (B);
- Participants had not undergone total knee replacement (e.g., TKA), to ensure consistency in natural disease monitoring.

Studies were excluded if:

- They were literature reviews, study protocols, or did not report original data;
- They focused primarily on interventions such as pharmacological therapy, acupuncture, or radiological diagnostics, unless these methods were explicitly integrated with wearable monitoring tools;
- The monitoring approach was limited to laboratory or clinical environments and lacked demonstrated potential for home or real-world application.

Data Extraction

Extracted data included general study information (title, author, country), participant characteristics (sample size, mean age, sex distribution, and Body Mass Index (BMI)), and study type (e.g., cross-sectional, feasibility, RCT). For the purpose of this review, studies with $n \leq 30$ were categorized as small-sample studies, based on statistical simulation literature indicating that a sample size of 30 is a commonly accepted threshold for achieving 80% statistical power under standard conditions [45]. Studies with $n > 30$ were considered moderate to large samples, with $n \geq 100$ typically regarded as large-scale observational studies. Additionally, participants aged 65 years or older were classified as older adults, in accordance with standard definitions used in geriatric epidemiology and clinical guidelines [30]. Experimental design-related data were classified into two components:

For the daily life monitoring system, the sensor name, sensor type (e.g., IMU, sEMG, RGB-D camera), body placement location (e.g., knee, wrist, ankle), and the measured physiological or biomechanical variables (e.g., joint position, muscle strength, HRV) were extracted.

For the daily monitoring, the method of symptom quantification (e.g., questionnaires or rating scales) was extracted, the specific name (e.g. Visual Analogue Scale(VAS)), the frequency or timing of administration (e.g., weekly, daily morning), and the symptom domains measured (e.g., pain, stiffness, fatigue, sleep quality).

Finally, the primary outcomes of each study (main findings) and the key symptoms of interest were also extracted. To synthesize the extracted variables in a structured and interpretable manner, all objective and subjective information were categorized into five domains. The categorization process was defined through discussion within the authors. The five categories are:

1. **Biomechanical and Functional Changes in Knee OA** – including joint kinematics, gait parameters, joint loading, and functional movement patterns.
2. **Muscle Strength, Postural Stability, and Pain Mediation** – including quadriceps strength, postural control metrics, and pain-related mediating factors.
3. **Symptoms and Sleep Interactions** – including fatigue, sleep quality, and their time-dependent relationships with pain.
4. **Physical Activity and Walking Patterns** – including activity level, step count, and energy expenditure.
5. **Physiological Markers and Knee OA Symptoms** – including heart rate variability (HRV), temperature, bioimpedance, and muscle tone/stiffness.

Each included study's outcome variables were mapped to one or more of these domains based on the primary physiological or functional target of the measurement. This categorization enabled the narrative synthesis of results around clinically meaningful symptom dimensions.

Procedure

All screening and data extraction procedures were conducted by a single reviewer (BC), with regular discussions and consensus meetings held with the authors to ensure consistency and reduce potential bias. Screening was supported by EndNote X9 for deduplication and manual review.

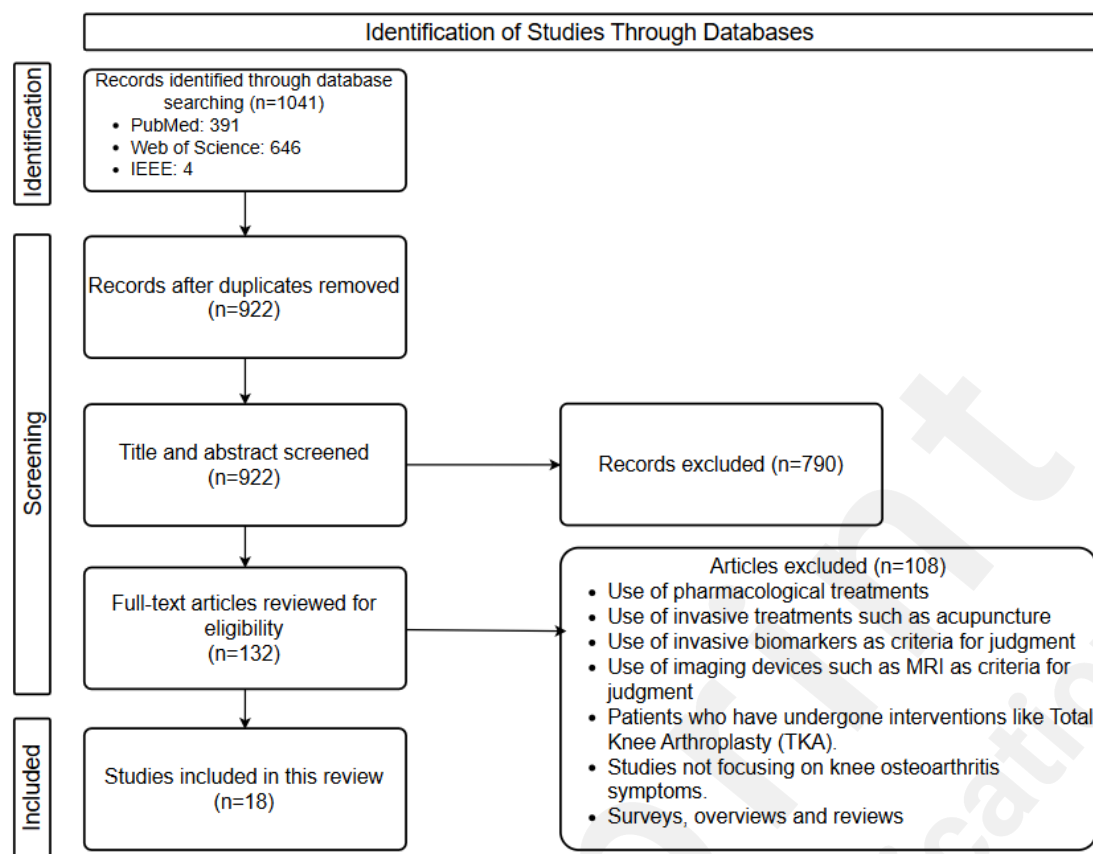
Titles and abstracts of all records retrieved from the databases were screened for relevance based on predefined inclusion and exclusion criteria. During this phase, any ambiguous cases were flagged and discussed with the research team to determine eligibility. A pilot round of screening was conducted on a small set of studies to refine the application of the criteria. After the title-abstract screening, full texts of the potentially eligible studies were retrieved and evaluated using the same decision process.

Following selection, data extraction was performed using a pre-structured charting form developed in consultation with the research team. The form was iteratively refined based on feedback during pilot testing on a subset of studies. Extracted data were then synthesized descriptively, using structured tables and narrative summaries.

Results

Search Results

Figure 1 shows the PRISMA flow diagram. Initially, an extensive search across multiple databases yielded 1041 records. After deduplication, the collection was reduced to 922 records (11.4% duplicates removed). After screening the title and abstract, 132 papers (14.3% of deduplicated records) remained for full text screening. Among the 114 articles excluded during full-text screening, 81 were excluded specifically because the monitoring methods were not considered feasible for daily life monitoring, following the predefined feasibility requirements: 8/81 were invasive; 40/81 were not portable/wearable etc. Finally, a total of 18 articles (1.7% of initial records; 13.6% of full-text articles) were included in this scoping review.



PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram.

Participant Characteristics, Symptom Focus, and Outcome Variables

Summary of Included Studies

ID	Year	Location	Sample Size	Age	Gender (M/F)	BMI	Symptoms	Type of Study	Main Findings
1[12]	2012	Japan	47	59.2 ± 5.98	15/32	22.7 ± 3.04	Pain & Stiffness	Feasibility	Range of knee joint trajectory (RKJT) in early KOA was greater than in controls during stair climbing.
2[13]	2019	US	160	71 ± 4	61/99	29.6 ± 3.4	Fatigue & Pain	Observational	Pain and fatigue varied diurnally.

ID	Year	Location	Sample Size	Age	Gender (M/F)	BMI	Symptoms	Type of Study	Main Findings
									Sleep quality significantly impacted fatigue, less so pain.
3[14]	2020	Brazil	11	63.1 ± 9.5	NA	28.7 ± 4	Pain	Cross-sectional	Affected knees had higher temperature, not associated with pressure pain thresholds.
4[15]	2021	Turkey	64	63.4 ± 8.8	NA	32.2 ± 4.9	Pain	Cross-sectional	HGS-ND was significantly correlated with radiological and functional outcomes.
5[16]	2021	Japan	21	72.1 ± 7.9	4/17	24.9 ± 3.4	Pain & Stiffness	Cross-sectional	Impaired self-perception of the knee related to reduced knee excursion during fast walking.
6[17]	2020	US	1666	67.2 ± 7.6	681/985	30.6 ± 5.7	Pain	Cross-sectional	Sex differences:

ID	Year	Location	Sample Size	Age	Gender (M/F)	BMI	Symptoms	Type of Study	Main Findings
									Men had stronger quadriceps; women had more pain and higher KL grades.
7[18]	2023	US	42	60.4 ± 12.6	14/28	30 ± 6.8	Pain	Cross-sectional	Higher peak tibial acceleration (PTA) linked to more knee pain and greater vertical loads.
8[19]	2021	US	30	58 ± 9	10/20	33.5 ± 5.8	Fatigue	Cross-sectional	Walking energetics were associated with physical activity; fatigue mediated the effect.
9[20]	2023	Saudi Arabia	95	66.4 ± 7.8	53/42	31.3 ± 7	Pain	Cross-sectional	Quadriceps strength negatively correlated with postural stability; pain was a key mediator.
10[21]	202	USA	28	57–	28/5	26.6	Pain	Cross-	Obesity in

ID	Year	Location	Sample Size	Age	Gender (M/F)	BMI	Symptoms	Type of Study	Main Findings
]	4			78		– 42.8		sectional	older adults was linked to more knee pain and greater loads during stair descent.
11[22]	2024	Germany	148	66 ± 25	80/68	32 ± 13	Pain	Cross-sectional	HRV slightly decreased in early KOA; significantly reduced in late-stage KOA.
12[23]	2024	UK	38	58 ± 9	5/33	NA	General symptoms	Feasibility	Usability of iKOALA mHealth app was tested over 12 weeks; improved health outcomes observed.
13[24]	2020	Belgium	19	65 ± 5.2	12/7	26 ± 2.2	Pain	Cross-sectional	Reduced trunk/pelvis rotation and knee flexion during gait; linked to perceived pain.
14[25]	2021	US	50	65.7 ±	13/37	34.4 ± 9.1	Pain & Stiffness	Reliability Study	Smartphone goniometer

ID	Year	Location	Sample Size	Age	Gender (M/F)	BMI	Symptoms	Type of Study	Main Findings
				10.1					apps were valid for assessing knee ROM in KOA or post-TKR patients.
15[26]	2022	US	10	75.6 ± 8.21	1/9	NA	Pain	Cross-sectional	Bioimpedance metrics can predict pain episodes in individuals with KOA.
16[27]	2021	Australia	65	61.3 ± 5.99	35/30	28.7 ± 28.66	Pain	RCT	Step count changes over 2 months were correlated with improvement and WOMAC scores.
17[28]	2024	China	30	59.73 ± 4.83	0/30	24.83 ± 2.66	Stiffness	Cross-sectional	Increased MG and LG stiffness associated with loading asymmetry and higher symptom severity.
18[29]	2024	China	40	65.28 ±	0/40	22.27 ±	Pain	Cross-sectional	FPI-6 score was

ID	Year	Location	Sample Size	Age	Gender (M/F)	BMI	Symptoms	Type of Study	Main Findings
				5.93		2.19			associated with quadriceps muscle performance changes.

Table 1 shows the general information extracted from the included papers. Seven studies (40%) were conducted in the United States. China and Japan each contributed 2 studies (11.1% each). The remaining studies were conducted in Australia, Brazil, Germany, Saudi Arabia, Turkey, the UK, and Belgium, with each country contributing one study (5.6%).

The sample sizes across studies ranged from 10 to 1666 participants. Several studies with small sample sizes[45] ($n \leq 30$) [14,16,19,21,24,26,28,29] primarily focused on detailed biomechanical evaluations. Such studies often involved complex motion capture setups, high-resolution kinetic and kinematic assessments, or laboratory-based measurement techniques. Studies with moderate sample sizes[45] ($n > 30$) [18,20,22,25] commonly investigated topics such as pain mechanisms, postural stability, and metabolic factors.

The mean age of participants varied across studies, ranging from 57 to 75 years. 15 studies involving persons (≥ 65 years) primarily focused on symptom fluctuations[14,15,17,21,22,23,27], sleep disturbances[13,25], and functional decline[16,18,20,21,23,24,26,29]. In contrast, 3 studies with younger persons (≤ 65 years) examined biomechanical parameters such as knee joint trajectory (RKJT) [12], muscle stiffness [28], and walking energetics [19].

Gender distribution across studies showed a notable imbalance, accounting for approximately 73.3% of the total (2479 participants) are female, while male participants represented 26.7% (900 participants). Only four studies including more male than female participants [20,22,24,27]. BMI was another critical demographic factor reported in 16 of the 18 studies. Most studies indicated participants were either overweight or obese.

In terms of symptoms, while pain remained the most frequently assessed outcome [12,14,17,18,20,21,24], other studies also captured fatigue [13,19], stiffness [16,25,28], and neuromuscular dysfunction [24,29].

The main findings of the included studies regarding the monitoring of knee OA symptoms and the employed sensor modalities to capture the symptoms can be categorized into the following thematic areas:

Biomechanical and Functional Changes in Knee OA

Individuals with knee OA demonstrated significant alterations in movement mechanics, including reduced

trunk rotation, internal pelvis rotation, and knee flexion range of motion (ROM)[24] during walking. Notably, diminished knee flexion at the end of the stance and swing phases was associated with increased pain perception. Additionally, those with unilateral knee OA exhibited higher medial gastrocnemius (MG) and lateral gastrocnemius (LG) stiffness[28] on the symptomatic side, correlating with altered lower limb loading patterns and increased symptom severity. Furthermore, the RKJT in early knee OA was significantly greater than in controls during steady stair climbing.[12] To assess alterations in movement mechanics and joint-level function, inertial measurement units (IMUs) were the most frequently used modality. IMUs were placed on various body locations, including the ankle [18], wrist [13,27], and the whole body [23], to capture gait speed, joint angular velocity, and dynamic motion trajectories. In two studies, force platforms were employed [21,28] to measure ground reaction forces and plantar pressure, enabling detailed kinetic analysis during walking and stair descent. RGB-D cameras, such as the Kinect v2, were also used [12] to quantify complex knee joint trajectories during functional tasks. Goniometers and dynamometers were combined in several studies [15,27] to evaluate knee ROM and joint torque production. In addition, muscle stiffness—particularly of the medial and lateral gastrocnemius—was assessed using the MyotonPRO device [28]. The WOMAC (n=5) [15,17,21,22,27,28] and KOOS (n=3) [19,24,27] scales were widely used to assess functional limitations, joint stiffness, and mobility restrictions caused by Knee OA. These tools allowed for a standardized evaluation of physical functioning.

Muscle Strength, Postural Stability, and Pain Mediation

Knee OA patients displayed significant negative correlations between quadriceps strength and postural stability parameters[20], with pain emerging as a critical mediator in this relationship. Additionally, quadriceps muscle performance was significantly associated with the Foot Posture Index-6 (FPI-6) total score, suggesting a potential link between foot posture and muscle function in Knee OA management. Studies investigating the interplay between muscle strength and postural control frequently utilized isokinetic dynamometers [15,16,26,27] to measure quadriceps force output under standardized conditions. Surface electromyography (sEMG) sensors, such as the Delsys Bagnoli system, were employed to record activation patterns of lower limb musculature [16]. Subjective scales like Visual Analog Scale (VAS) (n=4)[16,18,20,28] and Numeric Rating Scale (NRS) (n=4)[12,13,26,29] were frequently used to assess the intensity of pain experienced by participants.

Symptoms and Sleep Interactions

Pain and fatigue exhibited diurnal variations[13], with sleep quality playing a crucial role in symptom modulation. A night of good sleep was followed by lower morning pain and fatigue scores, although symptom severity later in the day remained similar regardless of sleep quality. Sleep disturbances had a greater effect on fatigue than pain intensity. Sensor-based monitoring of fatigue and sleep symptoms involved the use of wearable devices capable of capturing rest-activity cycles[13,19]. For example, the Actiwatch [13], worn on the wrist, was employed to track sleep duration and circadian rhythm disturbances. These objective sleep data

were complemented by self-reported sleep diaries, allowing for the exploration of relationships between nocturnal recovery and daytime symptom intensity.

Physical Activity and Walking Patterns

Walking energetics were significantly associated with physical activity levels, with fatigability mediating this effect[19]. Step count changes over two months demonstrated small but significant correlations with global improvement and Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) function scores.[27] Individuals with Knee OA who exhibited a higher peak tibial acceleration (PTA) during walking experienced greater knee pain and increased vertical load rates.[18] Additionally, among older adults with obesity and Knee OA, higher body mass was linked to greater knee pain and increased joint loads during stair descent.[21] To investigate physical activity behavior and its association with symptom burden, multiple studies implemented commercial activity trackers such as Fitbit devices and smartphone applications [13,18,19,23,27]. These tools enabled continuous monitoring of step counts, physical activity levels, and sedentary time across extended periods. Additionally, more advanced physiological monitoring tools, including the COSMED K5 system and Garmin chest-worn sensors [19], were used to evaluate oxygen uptake and walking energetics. IMU-based tools, such as the Blue Thunder unit, provided ankle-mounted acceleration data [18] to quantify PTA.

Physiological Markers and Knee OA Symptoms

Patients with knee OA exhibited higher knee temperature, although this was not directly associated with pressure pain thresholds[14]. Heart rate variability (HRV) was slightly reduced in early knee OA but significantly decreased in late-stage knee OA[22]. Moreover, bioimpedance metrics were identified as predictors of active pain experiences, offering a non-invasive method for assessing tissue composition and fluid distribution, which are relevant to inflammation and joint swelling in KOA[26]. Physiological variables relevant to systemic or localized inflammation and autonomic function were assessed using a combination of wearable biosensors. Infrared thermal sensors placed on the knee [14] allowed for the assessment of localized skin temperature, potentially reflecting inflammatory activity. HRV was captured through portable ECG devices such as KardiaMobile [22]. Bioimpedance analysis were implemented via knee wrap stabilizers with embedded sensors [26].

Study ID	Objective	Sensor Type	Placement	Measured Variable	Subjective Method	Tool Name	Frequency	Outcome
1[12]	Kinect v2	RGB-D	—	Knee joint position	Questionnaire	JKOM	Not specified	Pain score
2[13]	Actiwatch-Score	IMU	Wrist	Sleep quality	Subjective rating	11-point fatigue/p	Daily (5 days in	Fatigue & Pain score

Study ID	Objective Sensor	Sensor Type	Placement	Measured Variable	Subjective Method	Tool Name	Frequency	Outcome
						ain	total)	
3[14]	Infrared sensor	Temperature	Knee	Temperature	Pain pressure threshold	PPT	Once	Pain threshold
4[15]	Dynamometer	Force sensor	Knee	Muscle strength	Questionnaire	WOMAC	Once	Function limitation
5[16]	Goniometer, Dynamometer, IMU	Multisensor	Whole body	ROM, load	Scale	VAS	Not specified	Pain
6[17]	Delsys Bagnoli	sEMG	Lower limbs	Muscle activation	Questionnaire	WOMAC	Once	Pain and function
7[18]	IMU Blue Thunder	IMU	Ankle	Tibial acceleration	Scale	VAS	Not specified	Pain
8[19]	Garmin, COSMED K5	HRV, Oxygen uptake	Chest	Walking energetic s	Questionnaires	KOOS, PROMIS	Baseline + follow-up	Fatigue, Function
9[20]	Dynamometer	Force sensor	Knee	Muscle strength	Scale	VAS	Once	Pain score
10[21]	Force platform	Ground force	Ground	Kinematics	Questionnaire	WOMAC	Baseline + follow-up	Function
11[22]	KardiaMobile	ECG	Finger	HRV	Questionnaire	WOMAC	Once	Pain/function
12[23]	iKOALA, Fitbit	App, IMU	Wrist	Activity level	App + survey	MSK-HQ	Pre/post 1 week	Symptoms, Activity
13[24]	MVN	IMU	Whole body	Kinematics	Questionnaire	KOOS	Daily(7 days in total)	Pain, mobility
14[25]	Goniometer, Dynamometer	ROM tool	Knee	ROM, Strength	Numeric scale	QNPRS	Not specified	Pain

Study ID	Objective Sensor	Sensor Type	Placement	Measured Variable	Subjective Method	Tool Name	Frequency	Outcome
	ther							
15[26]	Thermal Knee Wrap	Bioimpedance	Knee	Structural changes	Phone call rating	0–4 scale	Unclear	Pain
16[27]	Fitbit Flex 2	IMU	Wrist	Load rate	Questionnaires	Mixed	Pre/post 2 month	Pain, function
17[28]	Force platform	Ground force	Ground	Plantar pressure	Scales	WOMAC, VAS	Twice	Pain, gait
18[29]	MyotonPRO	Dynamic stiffness	Lower body	Tone & stiffness	Index assessment	FPI-6	Once	Stiffness

Sensor Modalities and Measured Variables by Symptom Categories

The included studies employed a wide array of sensor modalities to capture the symptoms associated with knee OA. These modalities were organized into five categories based on the primary main findings.

Discussion

This scoping review synthesized findings from literature exploring the use of sensor technologies for monitoring knee OA symptoms in daily life settings. Current research provides valuable insights into biomechanical patterns, physiological indicators, and patient-reported outcomes.

Sensor Choice and Contextual Fit

Our review highlights a critical tension between the precision of lab-based instruments and the ecological validity of wearables in monitoring knee OA symptoms. While lab-based systems such as force platforms and dynamometers offer highly accurate biomechanical data, their application is often limited by the controlled environment in which they are used. In contrast, wearable sensors, such as Inertial Measurement Units (IMUs) and Electrocardiography (ECG) monitors, are more adaptable to real-world settings, allowing for daily monitoring of physical activity, gait patterns, and physiological responses.

Our findings suggest that a hybrid monitoring paradigm may be the optimal solution, combining the clinical validation for short-term validation with the long-term ecological data captured by wearables. Such a model would allow for accurate symptom tracking in real-life settings while ensuring that the data collected aligns with clinical standards. Moreover, emerging sensor modalities, such as bioimpedance and thermal imaging, offer exciting new opportunities to capture soft tissue changes and inflammatory responses, which could provide valuable insights into knee OA symptoms. These technologies are non-invasive and could potentially offer better contextual sensitivity in daily monitoring settings [14,26]. Future research should explore these modalities to assess their feasibility and clinical relevance in knee OA monitoring.

Rethinking Symptom Targets: Pain Is Not Enough

Pain has historically been the dominant focus in knee OA research, with most studies prioritizing pain severity as the primary outcome measure. However, our review reveals that other symptoms—such as fatigue and stiffness—play an equally significant role in the overall disability experienced by knee OA patients [12,13,16,19,25,29]. These findings align with current literature, which underscores the multifaceted nature of knee OA and its impact on both physical and mental well-being [12,29].

Many of the studies reviewed focused on pain as the primary symptom to monitor, yet this singular focus risks overlooking the broader symptom profile that affects patients' daily function and quality of life. Fatigue, in particular, was found to interact with pain intensity, exacerbating the disability experienced by patients [13], while neuromuscular dysfunctions, such as muscle stiffness and proprioception impairments, were also identified as significant contributors to mobility limitations [19,24].

Current approaches to knee OA monitoring as found in our review measure structural deterioration and joint-level biomechanics. However, knee OA is increasingly understood as a dynamic symptom ecology that spans musculoskeletal, neurological, behavioral, and psychosocial domains [46]. Pain, fatigue, sleep quality, and mobility limitations interact in complex, often non-linear ways. For instance, [13] showed that pain and fatigue exhibited diurnal variation, and were strongly influenced by sleep quality, underscoring the interdependence of these factors. Additionally, alterations in neuromuscular control and stiffness [24,28] demonstrated the need to evaluate multiple symptom dimensions simultaneously. Monitoring systems must therefore move beyond isolated metrics (e.g., gait speed or range of motion) and toward integrated models that capture day-to-day fluctuations and multi-dimensional symptom patterns.

Thus, it is essential for future monitoring systems to move beyond pain alone and integrate multidimensional assessment models that account for a range of symptom domains. This approach would guide the design of more comprehensive monitoring systems capable of capturing the complexity of knee OA symptoms in real-time. Our review emphasizes the need for such systems to align with recent understandings of knee OA as a systemic disorder with heterogeneous symptom trajectories. By incorporating both objective measurements (e.g., joint kinematics, muscle activation) and subjective data (e.g., fatigue, psychological distress), future sensor-based systems could offer more personalized, effective monitoring that better addresses the diverse needs of patients.

Monitoring Should Lead to Action: Closing the Feedback Loop

A key gap found in the current research in knee OA monitoring is the predominantly passive nature of sensor-based systems[49]. While numerous studies, including those reviewed here, have captured detailed movement and physiological data [15,23,27], few have translated these insights into real-time feedback loops. Our review found that most knee OA studies stop at reporting trends in activity or symptom severity, without enabling in-the-moment feedback based on patient state. This limitation is particularly evident in the context

of knee OA, where most studies focus on capturing trends in physical activity or symptom severity, without providing actionable insights that could trigger in-the-moment adjustments to a patient's care plan.

Interestingly, in other health contexts, such as cardiovascular disease or diabetes management, there are many examples of studies and wearable devices that offer real-time feedback on physical activity or physiological metrics (e.g., heart rate, glucose levels)[52,53,54]. Systems mentioned in these studies have integrated feedback mechanisms that guide users towards health-related behavioral changes. However, in knee OA, this type of real-time feedback is less common. Unlike conditions where daily physical metrics (e.g., steps, heart rate) can more directly guide interventions, knee OA symptom patterns are influenced by more complex biomechanical and physiological factors, making immediate feedback more challenging.

Moreover, while high-level monitoring (e.g., step count or general activity levels) is often included in knee OA studies, these approaches lack the necessary detail and specificity required for real-time interventions. For instance, basic step counting can inform activity levels but does not address the underlying joint stress, pain, or biomechanical changes that contribute to symptom variability in knee OA.

Additionally, current eHealth applications for Knee OA, such as the iKOALA mobile health app [23], do provide valuable support in terms of monitoring musculoskeletal health and symptoms. However, these applications typically focus on symptom tracking and general recommendations rather than providing continuous, objective feedback based on real-time sensor data. Although these apps help users manage their symptoms, they do so without the detailed objective monitoring of physical activity or joint function that could enable more personalized, real-time adjustments. This highlights an important gap in the integration of sensor-based technologies with actionable feedback, which could transform how knee OA is managed in everyday settings.

Future research should prioritize the development of adaptive monitoring architectures capable of supporting self-management (e.g., pain forecasting, activity pacing) and clinical decision-making (e.g., alerts for symptom worsening). Such systems have already demonstrated success in other health conditions where real-time monitoring and predictive feedback have been integrated into patient management plans, resulting in improved outcomes and patient engagement [52]. Wearable technologies in these areas have evolved from passive trackers into interactive health companions—tools that provide actionable insights, guide behavioral adaptations, and alert healthcare providers to changes in patient condition. It is hypothesized that similar real-time adaptive systems could be highly beneficial for knee OA, helping to address the complex and fluctuating nature of its symptoms, enhance personalized care, and improve overall patient quality of life.

Validating Sensor Data: Ensuring Clinical Relevance for Knee OA Monitoring

In our review, while we identified several sensor modalities capable of monitoring biomechanical and physiological markers, the majority of studies lacked clear validation of these metrics against clinical

outcomes such as structural change of the joint. Sensor data must be validated against clinically meaningful endpoints to ensure that the insights provided are relevant and actionable in the management of knee OA. This highlights a critical gap in the current research: the need for robust validation studies that directly link sensor-derived data with patient-reported outcomes (e.g., WOMAC, VAS) and clinical measures (e.g., structural changes). Thus, future studies should prioritize the validation of sensor data against these clinically meaningful endpoints to enhance the utility of monitoring systems for knee OA management.

Profiling the Person, Not Just the Joint

Demographic factors like sex, age, and BMI clearly influence knee OA symptoms, as evidenced by several studies included in this review, which found significant sex-based differences in pain perception and functional limitations [17,20]. However, categorical groupings alone, such as age and BMI, are insufficient for developing personalized care strategies. In our review, we observed that while some studies consider demographic factors, they often fail to integrate them with physiological and psychological variables for a more comprehensive understanding of symptom variability [13,28]. Future systems should construct individualized "symptom profiles" that combine physiological data (e.g., joint kinematics, muscle strength), activity patterns (e.g., walking energetics, step count), and psychological states (e.g., fatigue sensitivity, pain perception). These profiles would enable more targeted and precision-driven interventions. For example, a postmenopausal woman with high sensitivity to fatigue may require different monitoring parameters and interventions compared to an athletic male with early-stage joint degeneration, as demonstrated in previous research [12,19].

Strengths and Limitations

This scoping review provides a comprehensive synthesis of the current state of sensor-based monitoring technologies for knee OA symptoms. One of the major strengths of this review is its thorough examination of various sensor modalities, ranging from traditional biomechanical devices such as force platforms and dynamometers to wearable technologies like IMUs, ECG monitors, and emerging tools like bioimpedance sensors. This review offers as such valuable insights into the potential for integrating wearable sensors into personalized knee OA management.

Another key strength lies in the multidimensional approach taken in categorizing and evaluating the data captured by these sensors. Unlike previous reviews that may have focused primarily on pain monitoring, this review goes further by incorporating a wide range of symptoms, including fatigue and muscle stiffness. This approach aligns with the current understanding of knee OA as a systemic disorder with multifactorial symptom trajectories, ensuring that future monitoring frameworks are not limited to pain alone but take into account the full range of symptoms that contribute to functional impairment and quality of life.

This review also has limitations. Our search was limited to English-language publications and may have missed non-indexed or unpublished studies. Additionally, the field is rapidly evolving, and recent

technological innovations may not be captured. Nonetheless, this review offers a foundational synthesis to guide future development, emphasizing the need for adaptive, integrated, and feedback monitoring approaches.

Conclusion

This review consolidates the current state of literature on sensor-based monitoring of knee OA symptoms and identifies related key gaps and future directions. Sensor modalities employed for monitoring knee OA symptoms in real-world settings include IMUs, EMG sensors, temperature sensors, and physiological monitoring devices such as HRV monitors. The data collected through these modalities primarily includes biomechanical variables, physiological variables, and subjective data, including pain, fatigue, and sleep quality. While existing studies have successfully capturing biomechanical and physiological indicators, they often fall short in translating this data into actionable insights for the users to do just-in-time intervention. Moreover, symptoms such as fatigue, sleep disturbances, and psychological distress remain underrepresented in monitoring systems. To advance the field, future research should prioritize multidimensional symptom profiling into system design. In that way, sensor-based monitoring can move beyond passive observation and become a transformative tool in personalized Knee OA management.

PRISMA-ScR checklist

PRISMA-ScR Checklist for Reporting This Scoping Review

No.	Section	Item Description	Reported on Page
1	Title	Identify the report as a scoping review.	Title page
2	Abstract	Provide a structured summary that includes background, objectives, eligibility criteria, data sources, charting methods, and main results.	Abstract
3	Introduction: Rationale	Describe the rationale for the review in the context of what is already known.	p.1–2
4	Introduction: Objectives	Provide an explicit statement of the questions and objectives being addressed.	p.2
5	Methods: Eligibility criteria	Specify characteristics of sources of evidence (e.g., years considered, language, publication status) used as inclusion/exclusion criteria.	p.3
6	Methods: Information sources	Describe all information sources (e.g., databases with dates of coverage).	p.2-3
7	Methods: Search	Present the full electronic search strategy for at least one database.	Appendix
8	Methods: Selection of	State the process for selecting sources of	p.3-4

No.	Section	Item Description	Reported on Page
	sources	evidence (e.g., screening, eligibility, included).	
9	Methods: Data charting process	Describe the methods of charting data from the included sources.	p.3-4
10	Methods: Data items	List and define all variables for which data were sought.	p.3-4
11	Methods: Critical appraisal of sources (optional)	If done, provide rationale and describe methods used for assessing quality.	Not applicable
12	Methods: Synthesis of results	Describe the methods used to handle and summarize the charted data.	p.4
13	Results: Selection of sources	Provide number of sources screened, assessed for eligibility, and included, with reasons for exclusions.	Figure 1
14	Results: Characteristics of sources	Present characteristics of each source of evidence.	Table I
15	Results: Charting results	Present relevant data charted from included studies.	Table I-II
16	Results: Synthesis of results	Summarize the charting results as they relate to the review questions.	p.5-12
17	Discussion: Summary of evidence	Summarize main findings, their implications, and relevance to key groups.	p.12-14
18	Discussion: Limitations	Discuss the limitations of the scoping review process.	p.14
19	Conclusions	Provide a general interpretation of the results with respect to the review questions.	p.14
20	Funding	Describe sources of funding and role of funders.	Acknowledgements

Search Term

The following search terms were used for the literature review:

Pubmed Search Term

The following search term was used in Pubmed:

(((Knee Osteoarthritis[Title/Abstract])
AND ((Pain[Title/Abstract])
OR (Tenderness[Title/Abstract])) OR
(Knee OA[Title/Abstract]))
(Stiffness[Title/Abstract])
(Swelling[Title/Abstract]))

AND ((Monitoring[Title/Abstract]) OR (Measurement[Title/Abstract])
OR (Tracking[Title/Abstract]))

Web of Science Search Term

The following search term was used in Web of Science:

(TITLE-ABS("Knee Osteoarthritis") OR TITLE-ABS("Knee OA")) AND
(TITLE-ABS("Pain") OR TITLE-ABS("Stiffness") OR TITLE-ABS("Tenderness") OR TITLE-
ABS("Swelling")) AND
(TITLE-ABS("Monitoring") OR TITLE-ABS("Measurement") OR TITLE-ABS("Tracking"))

IEEE Xplore Search Term

The following search term was used in IEEE Xplore:

("Knee Osteoarthritis" OR "Knee OA") AND
("Pain" OR "Stiffness" OR "Tenderness" OR "Swelling") AND
("Monitoring" OR "Measurement" OR "Tracking")

References

- 1 Primorac D, Molnar V, Rod E, Jeleč Ž, Čukelj F, Matišić V, Vrdoljak T, Hudetz D, Hajsok H, Borić I. Knee Osteoarthritis: A Review of Pathogenesis and State-Of-The-Art Non-Operative Therapeutic Considerations. *Genes* (Basel). 2020 Jul 26;11(8):854. doi: 10.3390/genes11080854. PMID: 32722615; PMCID: PMC7464436.
- 2 Giaretta S, Magni A, Migliore A, Natoli S, Puntillo F, Ronconi G, Santoiemma L, Sconza C, Viapiana O, Zanolì G. A Review of Current Approaches to Pain Management in Knee Osteoarthritis with a Focus on Italian Clinical Landscape. *J Clin Med*. 2024 Aug 31;13(17):5176. doi: 10.3390/jcm13175176. PMID: 39274389; PMCID: PMC11396710.
- 3 Thirumaran AJ, Devezza LA, Atukorala I, Hunter DJ. Assessment of Pain in Osteoarthritis of the Knee. *J Pers Med*. 2023 Jul 14;13(7):1139. doi: 10.3390/jpm13071139. PMID: 37511752; PMCID: PMC10381750.
- 4 Thirumaran AJ, Devezza LA, Atukorala I, Hunter DJ. Assessment of Pain in Osteoarthritis of the Knee. *J Pers Med*. 2023 Jul 14;13(7):1139. doi: 10.3390/jpm13071139. PMID: 37511752; PMCID: PMC10381750.
- 5 Kraus VB, Sprow K, Powell KE, Buchner D, Bloodgood B, Piercy K, George SM, Kraus WE; 2018 PHYSICAL ACTIVITY GUIDELINES ADVISORY COMMITTEE*. Effects of Physical Activity in Knee and Hip Osteoarthritis: A Systematic Umbrella Review. *Med Sci Sports Exerc*. 2019 Jun;51(6):1324-1339. doi: 10.1249/MSS.0000000000001944. PMID: 31095089; PMCID: PMC6527143.
- 6 Cho Y, Jung B, Lee YJ, Kim MR, Kim EJ, Sung WS, Ha IH. Association between sleep duration and osteoarthritis and their prevalence in Koreans: A cross-sectional study. *PLoS One*. 2020 Apr 27;15(4):e0230481. doi: 10.1371/journal.pone.0230481. PMID: 32339178; PMCID: PMC7185595.
- 7 Hunter DJ, March L, Sambrook PN. Knee osteoarthritis: the influence of environmental factors. *Clin Exp Rheumatol*. 2002 Jan-Feb;20(1):93-100. PMID: 11892719.

- 8 Steultjens MP, Dekker J, van Baar ME, Oostendorp RA, Bijlsma JW. Range of joint motion and disability in patients with osteoarthritis of the knee or hip. *Rheumatology (Oxford)*. 2000 Sep;39(9):955-61. doi: 10.1093/rheumatology/39.9.955. PMID: 10986299.
- 9 Sohn R, Assar T, Kaufhold I, Brenneis M, Braun S, Junker M, Zaucke F, Pongratz G, Jenei-Lanzl Z. Osteoarthritis patients exhibit an autonomic dysfunction with indirect sympathetic dominance. *J Transl Med*. 2024 May 16;22(1):467. doi: 10.1186/s12967-024-05258-9. PMID: 38755685; PMCID: PMC11100157.
- 10 Patterson BE, Girdwood MA, West TJ, Bruder AM, Øiestad BE, Juhl C, Culvenor AG. Muscle strength and osteoarthritis of the knee: a systematic review and meta-analysis of longitudinal studies. *Skeletal Radiol*. 2023 Nov;52(11):2085-2097. doi: 10.1007/s00256-022-04266-4. Epub 2022 Dec 23. PMID: 36562820.
- 11 Wise BL, Niu J, Zhang Y, Wang N, Jordan JM, Choy E, Hunter DJ. Psychological factors and their relation to osteoarthritis pain. *Osteoarthritis Cartilage*. 2010 Jul;18(7):883-7. doi: 10.1016/j.joca.2009.11.016. Epub 2010 Mar 24. PMID: 20346403; PMCID: PMC2912218.
- 12 Ogawa A, Iijima H, Takahashi M. Identification of Early Knee Osteoarthritis Based on Knee Joint Trajectory during Stair Climbing. *Int J Environ Res Public Health*. 2022;19(22). Epub 20221115. doi: 10.3390/ijerph192215023. PubMed PMID: 36429742; PubMed Central PMCID: PMC9691255.
- 13 Whibley D, Braley TJ, Kratz AL, Murphy SL. Transient Effects of Sleep on Next-Day Pain and Fatigue in Older Adults With Symptomatic Osteoarthritis. *J Pain*. 2019;20(11):1373-82. Epub 20190511. doi: 10.1016/j.jpain.2019.04.011. PubMed PMID: 31085335.
- 14 Alfieri FM, Vargas ESNCO, Dos Santos ACA, Battistella LR. Cutaneous temperature and pressure pain threshold in individuals with knee osteoarthritis. *Reumatologia*. 2020;58(5):272-6. Epub 20201029. doi: 10.5114/reum.2020.100195. PubMed PMID: 33227096; PubMed Central PMCID: PMC7667939.
- 15 Kulakli F, Sari IF. Is there a relationship between hand grip strength and knee osteoarthritis in terms of radiological and functional findings in female patients? *Arch Rheumatol*. 2021;36(3):389-97. Epub 20210208. doi: 10.46497/ArchRheumatol.2021.8560. PubMed PMID: 34870171; PubMed Central PMCID: PMC8612487.
- 16 Toda H, Maruyama T, Fujita K, Yamauchi Y, Tada M. Self-Perception of the Knee Is Associated with Joint Motion during the Loading Response in Individuals with Knee Osteoarthritis: A Pilot Cross-Sectional Study. *Sensors (Basel)*. 2021;21(12). Epub 20210610. doi: 10.3390/s21124009. PubMed PMID: 34200714; PubMed Central PMCID: PMC8229136.
- 17 Sisante JF, Wang N, Felson DT, Nevitt MC, Lewis CE, Frey-Law L, et al. Influence of Antagonistic Hamstring Coactivation on Measurement of Quadriceps Strength in Older Adults. *PM R*. 2020;12(5):470-8. Epub 20191125. doi: 10.1002/pmjr.12253. PubMed PMID: 31585496; PubMed Central PMCID: PMC8016551.

- 18 James KA, Corrigan P, Lanois C, Huang CH, Davis IS, Stefanik JJ. Association of tibial acceleration during walking to pain and impact loading in adults with knee osteoarthritis. *Clin Biomech (Bristol)*. 2023;109:106097. Epub 20230917. doi: 10.1016/j.clinbiomech.2023.106097. PubMed PMID: 37738920; PubMed Central PMCID: PMC10565571.
- 19 Foucher KC, Aydemir B, Huang CH. Walking energetics and fatigue are associated with physical activity in people with knee osteoarthritis. *Clin Biomech (Bristol)*. 2021;88:105427. Epub 20210717. doi: 10.1016/j.clinbiomech.2021.105427. PubMed PMID: 34303950; PubMed Central PMCID: PMC9841508.
- 20 Alshahrani MS, Reddy RS. Quadriceps Strength, Postural Stability, and Pain Mediation in Bilateral Knee Osteoarthritis: A Comparative Analysis with Healthy Controls. *Diagnostics (Basel)*. 2023;13(19). Epub 20231001. doi: 10.3390/diagnostics13193110. PubMed PMID: 37835853; PubMed Central PMCID: PMC10573007.
- 21 Rice PE, Pate GA, Hill RD, DeVita P, Messier SP. The association between obesity, knee pain, and gait during stair descent in older adults with knee osteoarthritis. *Clin Biomech (Bristol)*. 2024;114:106228. Epub 20240312. doi: 10.1016/j.clinbiomech.2024.106228. PubMed PMID: 38518651.
- 22 Sohn R, Assar T, Kaufhold I, Brenneis M, Braun S, Junker M, et al. Osteoarthritis patients exhibit an autonomic dysfunction with indirect sympathetic dominance. *J Transl Med*. 2024;22(1):467. Epub 20240516. doi: 10.1186/s12967-024-05258-9. PubMed PMID: 38755685; PubMed Central PMCID: PMC11100157.
- 23 Stevenson RDM, Chowdhury EA, Lobo J, Western MJ, Bilzon JJ. Influence of the intelligent knee osteoarthritis lifestyle app (iKOALA) on knee joint pain. *BMC Musculoskelet Disord*. 2024;25(1):90. Epub 20240124. doi: 10.1186/s12891-024-07198-3. PubMed PMID: 38263125; PubMed Central PMCID: PMC10807134.
- 24 van der Straaten R, Wesseling M, Jonkers I, Vanwanseele B, Bruijnes A, Malcorps J, et al. Functional movement assessment by means of inertial sensor technology to discriminate between movement behaviour of healthy controls and persons with knee osteoarthritis. *J Neuroeng Rehabil*. 2020;17(1):65. Epub 20200519. doi: 10.1186/s12984-020-00694-2. PubMed PMID: 32430036; PubMed Central PMCID: PMC7236325.
- 25 Mehta SP, Bremer H, Cyrus H, Milligan A, Oliashirazi A. Smartphone goniometer has excellent reliability between novice and experienced physical therapists in assessing knee range of motion. *J Bodyw Mov Ther*. 2021;25:67-74. Epub 20201116. doi: 10.1016/j.jbmt.2020.11.021. PubMed PMID: 33714514.
- 26 Critcher S, Parmelee P, Freeborn TJ. Localized Multi-Site Knee Bioimpedance as a Predictor for Knee Osteoarthritis Associated Pain Within Older Adults During Free-Living. *IEEE Open J Eng Med Biol*. 2023;4:1-10. Epub 20230313. doi: 10.1109/OJEMB.2023.3256181. PubMed PMID: 37138591; PubMed Central PMCID: PMC10151013.
- 27 Yu SP, Ferreira ML, Duong V, Caroupapoulle J, Arden NK, Bennell KL, et al. Responsiveness of an

activity tracker as a measurement tool in a knee osteoarthritis clinical trial (ACTIVE-OA study). *Ann Phys Rehabil Med*. 2022;65(5):101619. Epub 20220214. doi: 10.1016/j.rehab.2021.101619. PubMed PMID: 34879312.

28 Wang W, Li F, Guo J, Zhang Z. Changes in gastrocnemius MTU stiffness and their correlation with plantar pressure in patients with knee osteoarthritis. *Front Bioeng Biotechnol*. 2024;12:1378031. Epub 20240509. doi: 10.3389/fbioe.2024.1378031. PubMed PMID: 38784765; PubMed Central PMCID: PMC1111847.

29 Shen X, Wang S, Chen J, Li J, Li C, Xiang R, et al. Inter-rater reliability and test-retest reliability of the foot posture index (FPI-6) for assessing static foot posture in elderly female patients with knee osteoarthritis and its association with quadriceps muscle tone and stiffness. *Front Bioeng Biotechnol*. 2024;12:1385986. Epub 20240621. doi: 10.3389/fbioe.2024.1385986. PubMed PMID: 38983600; PubMed Central PMCID: PMC11232489.

30 Singh S, Bajorek B. Defining 'elderly' in clinical practice guidelines for pharmacotherapy. *Pharm Pract (Granada)*. 2014 Oct;12(4):489. doi: 10.4321/s1886-36552014000400007. Epub 2014 Mar 15. PMID: 25580172; PMCID: PMC4282767.

31 Coggon, D., Reading, I., Croft, P. et al. Knee osteoarthritis and obesity. *Int J Obes* 25, 622–627 (2001). <https://doi.org/10.1038/sj.ijo.0801585>

32 Geng R, Li J, Yu C, Zhang C, Chen F, Chen J, Ni H, Wang J, Kang K, Wei Z, Xu Y, Jin T. Knee osteoarthritis: Current status and research progress in treatment (Review). *Exp Ther Med*. 2023 Aug 25;26(4):481. doi: 10.3892/etm.2023.12180. PMID: 37745043; PMCID: PMC10515111.

33 Raud, B., Gay, C., Guiguet-Auclair, C. et al. Level of obesity is directly associated with the clinical and functional consequences of knee osteoarthritis. *Sci Rep* 10, 3601 (2020). <https://doi.org/10.1038/s41598-020-60587-1>

34 Zullig, L.L., Bosworth, H.B., Jeffreys, A.S. et al. The association of comorbid conditions with patient-reported outcomes in Veterans with hip and knee osteoarthritis. *Clin Rheumatol* 34, 1435–1441 (2015). <https://doi.org/10.1007/s10067-014-2707-y>

35 Migliore A, Gigliucci G, Alekseeva L, et al. Treat-to-target strategy for knee osteoarthritis. International technical expert panel consensus and good clinical practice statements. *Ther Adv Musculoskelet Dis*. 2019;11:1759720X19893800. Published 2019 Dec 19. doi:10.1177/1759720X19893800

36 Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. *Ann Intern Med*. Oct 02, 2018;169(7):467-473.

37 Szilagyi IA, Waarsing JH, van Meurs JBJ, Bierma-Zeinstra SMA, Schiphof D. A systematic review of the sex differences in risk factors for knee osteoarthritis. *Rheumatology (Oxford)*. 2023;62(6):2037-2047. doi:10.1093/rheumatology/keac688

- 38 Kobsar D, Masood Z, Khan H, Khalil N, Kiwan MY, Ridd S, Tobis M. Wearable Inertial Sensors for Gait Analysis in Adults with Osteoarthritis—A Scoping Review. *Sensors*. 2020; 20(24):7143. <https://doi.org/10.3390/s20247143>
- 39 Cudejko T, Button K, Willott J, Al-Amri M. Applications of Wearable Technology in a Real-Life Setting in People with Knee Osteoarthritis: A Systematic Scoping Review. *Journal of Clinical Medicine*. 2021; 10(23):5645. <https://doi.org/10.3390/jcm10235645>
- 40 Cudejko T, Button K, Willott J, Al-Amri M. Applications of Wearable Technology in a Real-Life Setting in People with Knee Osteoarthritis: A Systematic Scoping Review. *Journal of Clinical Medicine*. 2021; 10(23):5645. <https://doi.org/10.3390/jcm10235645>
- 41 Kobsar D, Masood Z, Khan H, Khalil N, Kiwan MY, Ridd S, Tobis M. Wearable Inertial Sensors for Gait Analysis in Adults with Osteoarthritis—A Scoping Review. *Sensors*. 2020; 20(24):7143. <https://doi.org/10.3390/s20247143>
- 42 Cudejko T, Button K, Willott J, Al-Amri M. Applications of Wearable Technology in a Real-Life Setting in People with Knee Osteoarthritis: A Systematic Scoping Review. *Journal of Clinical Medicine*. 2021; 10(23):5645. <https://doi.org/10.3390/jcm10235645>
- 43 Johnson AJ, Palit S, Terry EL, et al. Managing osteoarthritis pain with smart technology: a narrative review. *Rheumatol Adv Pract*. 2021;5(1):rkab021. Published 2021 Mar 16. doi:10.1093/rap/rkab021
- 44 Hamilton DF, Akhtar S, Griffiths B, Prior Y, Jones RK. The use of technology to support lifestyle interventions in knee osteoarthritis: A scoping review. *Osteoarthr Cartil Open*. 2023;5(2):100344. Published 2023 Feb 9. doi:10.1016/j.ocarto.2023.100344
- 45 Serdar CC, Cihan M, Yücel D, Serdar MA. Sample size, power and effect size revisited: simplified and practical approaches in pre-clinical, clinical and laboratory studies. *Biochem Med (Zagreb)*. 2021;31(1):010502. doi:10.11613/BM.2021.010502
- 46 Overton M, Swain N, Falling C, Gwynne-Jones D, Fillingim R, Mani R. Understanding the biopsychosocial knee osteoarthritis pain experience: an ecological momentary assessment. *Pain Rep*. 2024;9(4):e1172. Published 2024 Jul 12. doi:10.1097/PR9.0000000000001172
- 47 Michie, S., van Stralen, M.M. & West, R. The behaviour change wheel: A new method for characterising and designing behaviour change interventions. *Implementation Sci* 6, 42 (2011). <https://doi.org/10.1186/1748-5908-6-42>
- 48 Jones CL, Jensen JD, Scherr CL, Brown NR, Christy K, Weaver J. The Health Belief Model as an explanatory framework in communication research: exploring parallel, serial, and moderated mediation. *Health Commun*. 2015;30(6):566-576. doi:10.1080/10410236.2013.873363

- 49 Xu S, Kim J, Walter JR, Ghaffari R, Rogers JA. Translational gaps and opportunities for medical wearables in digital health. *Sci Transl Med*. 2022;14(666):eabn6036. doi:10.1126/scitranslmed.abn6036
- 50 Rutherford D, Baker M, Wong I, Stanish W. The effect of age and knee osteoarthritis on muscle activation patterns and knee joint biomechanics during dual belt treadmill gait. *J Electromyogr Kinesiol*. 2017 Jun;34:58-64. doi: 10.1016/j.jelekin.2017.04.001. Epub 2017 Apr 7. PMID: 28411486.
- 51 Clynes MA, Jameson KA, Edwards MH, Cooper C, Dennison EM. Impact of osteoarthritis on activities of daily living: does joint site matter?. *Aging Clin Exp Res*. 2019;31(8):1049-1056. doi:10.1007/s40520-019-01163-0
- 52 Rodriguez-León C, Villalonga C, Munoz-Torres M, Ruiz JR, Banos O. Mobile and Wearable Technology for the Monitoring of Diabetes-Related Parameters: Systematic Review. *JMIR Mhealth Uhealth*. 2021 Jun 3;9(6):e25138. doi: 10.2196/25138. PMID: 34081010; PMCID: PMC8212630.
- 53 Ahmed A, Aziz S, Abd-Alrazaq A, Farooq F, Househ M, Sheikh J. The Effectiveness of Wearable Devices Using Artificial Intelligence for Blood Glucose Level Forecasting or Prediction: Systematic Review. *J Med Internet Res*. 2023;25:e40259. Published 2023 Mar 14. doi:10.2196/40259
- 54 Alzghaibi H. Perspectives of people with diabetes on AI-integrated wearable devices: perceived benefits, barriers, and opportunities for self-management. *Front Med (Lausanne)*. 2025 Apr 23;12:1563003. doi: 10.3389/fmed.2025.1563003. PMID: 40337275; PMCID: PMC12055762.