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Wearable Sensors in Knee Rehabilitation: A Narrative Review

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Abstract:- Only a few trustworthy assessment tools are available in clinical settings to track knee joint rehabilitation. Rehabilitation of Musculoskeletal injuries continue to adopt and evolve based on the recent evidence, patient needs and emerging technology. Wearable technology has significant clinical applications in diagnosis, documentation, remote monitoring and training. While there are various studies exploring the development, efficacy and accuracy of wearable tech, understanding the clinical application and usefulness of the tech can help its integration into clinical practice better. PUBMED, Springer, and IEEE were searched for eligible studies. With high reliability coefficients, large bounds of agreement, or only a few noticeable errors, all investigations produced good outcomes. They either misreported crucial facts or employed alternative or partially unsuitable approaches for measuring reliability. As a result, a mild risk of bias must be taken into account. In order to synthesis the evidence and make clear recommendations for the clinical usage of wearable movement sensors in knee joint rehabilitation, more quality criterion studies in clinical settings are required.Inertial sensors equipped with tri-axial accelerometers, gyroscopes, and magnetometers is the most common sensor technology that was used in research. Most of the studies have used the tech to analyze gait parameters. The sensor placements were mostly consistent for gait analysis. The overall population studied was minimal, this included a mix of healthy population without preexisting injuries. The tech was easy to adopt and cost effective, however the protocols for measurements could be standardized for routine clinical practice.

Keywords:- *Wearable Sensors, Knee Joint, Outcome Measure, Technologies, Knee Joint, Rehabilitation.*

I. INTRODUCTION

One of the most prevalent musculoskeletal diseases, knee pain can be brought on by ageing, acute injury, recurrent stress, and wear and tear of the soft tissues surrounding the knee. Variations in walking dynamics and muscle coordination have been linked to knee pain, according to studies.[27-29] Some common conditions of the knees that cause knee pain include knee osteoarthritis, anterior cruciate ligament tears, meniscus tear, iliotibial band syndrome and patellofemoral joint syndrome. Studies suggest that Knee Osteoarthritis is more prevalent among women, the elderly population, and obese people. The prevalence of knee Osteoarthritis in India is mainly in the population above the age of 60 years, of which 43% are women and 25% men [23]. Studies have found that about 12% of runners per year suffer from Iliotibial band syndrome (ITBS) caused due to overuse of the lateral knee. ITBS also affects cyclists, ballet dancers, and military recruits [24]. In the United States, it is reported that approximately 80,000 injuries are due to rupture of the anterior cruciate ligament (ACL). Individuals deficient in ACL knee suffer from chronic joint diseases such as articular cartilage damage [25].

Physicians initially advise patients with knee pain brought on by any of the aforementioned ailments to rest in order to alleviate excessive strain on the knee and stop further injury. Exercise-based therapy is typically used as the initial line of treatment for knee pain, followed for individuals with severe cases by acetaminophen and nonsteroidal anti-inflammatory medications (NSAIDs) and active rehabilitation. If the need to prevent joint overuse is evident, braces and orthoses are acceptable therapy options. Injections of hyaluronic acid and intra-articular corticosteroids are frequently used to treat osteoarthritis of the knee [30] Although rehabilitation is crucial for reducing knee pain, patients' adherence to rehabilitation and physiotherapy is generally poor. Low self-efficacy, inadequate social support or activity, melancholy, anxiety, and a sense of helplessness are just a few of the characteristics that have been demonstrated in studies to be barriers to treatment adherence [33]. Remote rehabilitation and monitoring may improve patient adherence to therapies in certain circumstances.

Wearable Sensor is an electronic device that can be worn on the body for sensing clinically relevant outcome measures. There is rapid adaptation in the field of wearable technology because of the technology’s small form factor, less power consumption and portability and ease of wearing on multiple locations as per the users’ demand. Wearable devices are equipped with an array of sensors that capture an individual's physiological and biomechanical traits, thus aiding in long time-monitoring, analysis, and interventions that were previously restricted to medical clinics and laboratories [34-35] According to some study, the usage of wearable sensors has helped the area of rehabilitation improve significantly. Over the past few years, there has also been a tremendous increase in interest in the use of wearable sensors for remote patient monitoring and telepresence. Wearable sensors have advanced in their capabilities to monitor, access, and offer feedback, which has made them dependable and crucial in clinical settings [31-32].

Wearable sensing systems are vital and promising for studying and analyzing the aforementioned knee disorders. A specific miniaturized, robust, and lightweight sensor-namely inertial motion sensor especially paves the way to record several outcome measures of the knees including range of motion angles, balance, spatio- temporal parameters of the knees including gait analysis, knee angle, knee velocity, knee force limits, etc. Moreover, readily available mono- packaging of accelerometers, gyroscopes, and magnetometers into a single inertial measurement unit (IMU) has made it more convenient for technology developers to develop mobile knee measurement systems at least cost and highest accuracy[26]. Wearable sensing systems are becoming popular and more researchers and institutes are incorporating these in their clinical applications.

- *Objectives*

The study's objective is to examine the outcome parameters these technologies monitor and comprehend their therapeutic value. The importance and requirements of the parameters in clinical practise are used to evaluate their clinical relevance. Reviewing the wearable technologies now in use for evaluating and tracking knee health in a variety of pathological states is the goal of this study.

II. METHODOLOGY

- *Literature Survey Criteria*

A literature survey was conducted for articles published in the databases PUBMED, Springer, and IEEE.

- *Exclusion and Inclusion Criteria*

Table 1 Exclusion and Inclusion Criteria

Inclusion criteria	Exclusion criteria
Studies involving individuals who had total knee replacement surgery, anterior cruciate ligament restoration, or knee osteoarthritis studies involving subjects that underwent at least one IMU investigation studies use sensors put on the body The quality of the data must be measured in some way. The articles published after the year of 2012 Articles that involve wearable sensors or sensing system focusing on knee health monitoring	Studies examining the use of intraoperative sensors to improve surgical results, such as employing pressure sensors during total knee replacement Studies that don't use wearable sensing equipment for postoperative digital treatments or telerehabilitation Cadavaric research studies including people who had rheumatic or neurological conditions that affected their balance or ability to walk articles reporting EMG studies All lab-based biomechanical studies involving the use of robots were not taken as a part of the review study. The research papers involving camera-based gait measures, prevention and feedback technologies, assistive devices, or robotics were eliminated.

- *Data Extraction*

A total of 2623 research articles were retrieved from the databases (PUBMED - 2324, Springer - 138, IEEE – 161). 364 articles were remaining after exclusion based on titles (PUBMED - 189, Springer - 88, IEEE - 87). After the exclusion of articles based on their abstracts, there were a total of 41 articles (PUBMED - 29, Springer - 3, IEEE - 9). The detailed exclusion and inclusion criteria were considered and 22 articles were finalized for the data synthesis and review study.

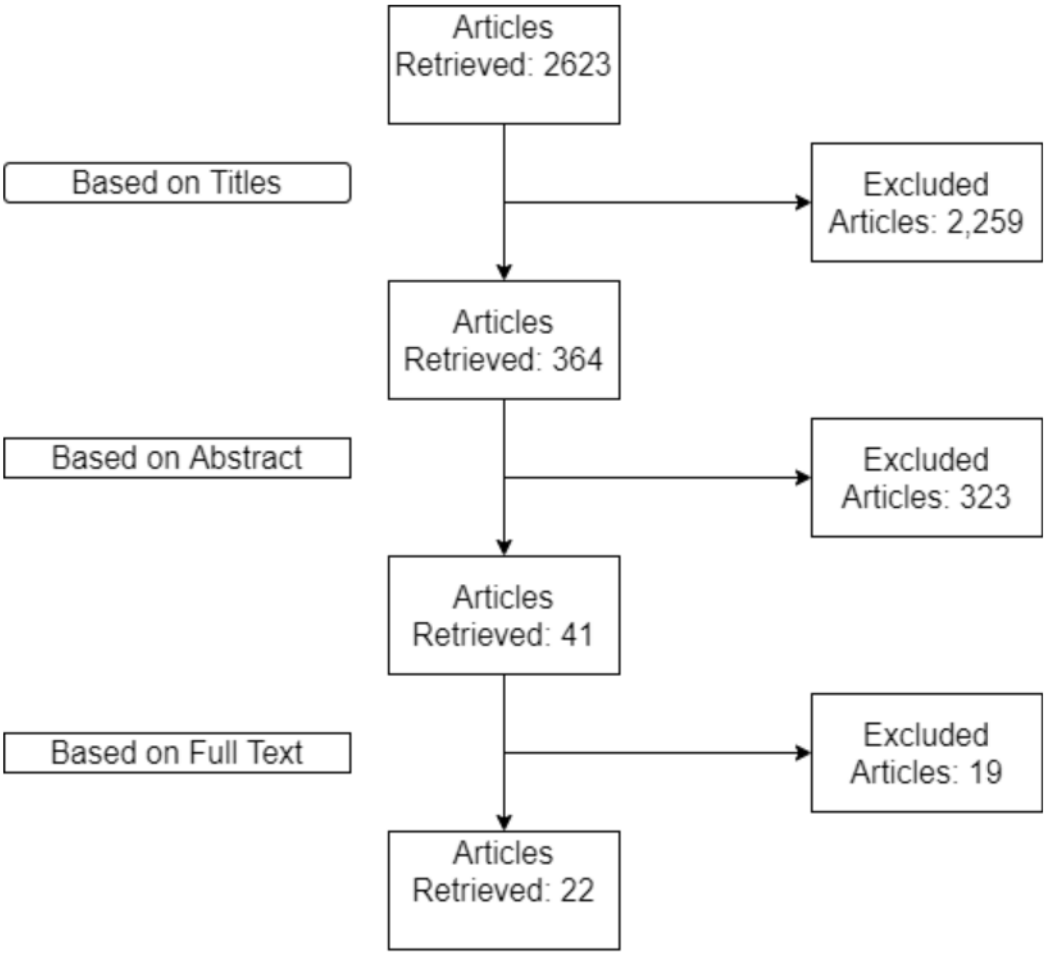

Fig 1 Data Extraction

III. RESULT

Table 2 Results

Sr. No.	Title	no. of sensors and sensor placement	Sensor Tech	outcome measures	Accessibility (Cost, Ease, Integration with other device, Location)
1	Clinical Evaluation of a Mobile Sensor-Based Gait Analysis Method for Outcome Measurement after Knee Arthroplasty	No.3 1- lower back 1- thigh 1-shank Placement- Thigh , shank and lumbosacral junction	The sensor consisted of accelerometers, gyroscopes and magnetometers. only gyroscopes were used to measure the outcomes because	gait analysis (mean values) parameters during stair climbing before and post surgery , Knee velocity angle, Knee angle curves	Integration : Sensor data were recorded and synchronised using self-developed software which is developed in the platform-independent programming language Java using the RXTX interface standard for the Bluetooth® connection; software and hardware architecture Location and Ease : Sensor was secured with therapeutic tape and placed on thigh and shank. The sensing system is small and does not occupy much region of the body and is wireless.

2	Detection of Knee Power Deficits following ACL Reconstruction Using Wearable Sensors	No. 2- thigh muscles of both the legs Placement- Mid lateral thighs	IMU principle variable- gyroscope acc and mag increase accuracy	ROC curve analysis Sensitivity and specificity of thigh angular velocity ratios	Integration: Kinematics and force data data were collected using a marker-based, 11 109 camera motion capturing system , Analyzed using MATLAB Location and Ease: Sensors and Tracking marker clusters were affixed around the thighs on the rigid plates firmly using elastic Velcro® straps and tape. Wireless system and just occupies mid lateral thighs.
3	Biometric Database for Human Gait Recognition using Wearable Sensors and a Smartphone	5 shimmer modules upper pocket pant pocket hand bag leg 1 samsung galaxy note Placement- Leg, Hand wrist, pant pocket Shirt pocket bag (left and right side)	shimmer modules- MEMS 2 axis accelerometer and gyroscope galaxy note- accelerometer and gyroscope	Gait analysis (slow, normal and fast walk)	Integration: The shimmer sensor and Samsung galaxy note were connected via Bluetooth and software used Multi Shimmer, Sync Sensor Pro list respectively Location and Ease: The 5 wearable shimmer sensors used were placed in multiple locations (mentioned in sensor placement column) and subjects carried the samsung galaxy note phone in their hands. Wireless technology,though the sensors were placed in multiple locations ,but they occupied a small region.
4	Monitoring and Assessment of Rehabilitation Progress on Range of Motion After Total Knee Replacement by Sensor-Based System	No.2 1 thigh 1 ankle Placement- Thigh Ankle	3 axis accelerometer and gyroscope	Joint ROM after completiong the rehabilitation was 20 time more than the impaired range of motion.	Integration: IMU sensor data were acquired real-time using application in android phone along with fuzzy c-means to identify the centroid of the acceleration signals as an equivalent ROM can be calculated. Location and Ease : Sensor , markers and wand were placed in thigh and ankle
5	Concurrent validity and inter trial reliability of a single inertial measurement unit for spatial-temporal gait parameter analysis in patients with recent total hip or total knee arthroplasty	No.19 1-Sacrum 2-Rt and Lt ASIA 2-Rt and Lt GT 2-Rt and Lt thigh 2- Rt and Lt external femoral condyle 2- Rt and Lt head of fibula 2- Rt and Lt mid of leg 2- Rt and Lt external	A tri-axial gyroscopeand a GPS receiver combined through advanced Sensor Fusion technology gait analysis used in this study is the optoelectronic MoCap system SMART D	All the gait parameters like cadence, speed, stride length,gait cycle duration, stance phase, swing phase , double support phase, single support phase.	Integration : IMU system tested in this study was the G-WALK®,equipped with a Bluetooth connection that allows the transmission of the recorded data to the dedicated software, G-Studio® Location and Ease :- Markers were placed according to the simple Davis protocol, which is a modified Davis protocol consisting of a 19 marker application on the pelvis and lower limbs excluding the shoulder girdle For healthy patients the markers were placed directly on skin.

		malleolus 2- Rt and LT heel Placement-Pelvic,hip leg, thigh,shine,Ankle			
6	Predicting Knee Joint Kinematics from Wearable Sensor Data in People with Knee Osteoarthritis and Clinical Considerations for Future Machine Learning Models	No.4 2 GT tibia and talocrural joint Placement-Lateral pelvic, lateral thigh, thigh and anterior shin	3 axis accelerometer and gyroscope 3-D motion analysis with 18 camera Vicon	4 trials of stand-to-sit, 4 trials of sit-to-stand, 3 trials of 3-stair ascent, 3 trials of 3-stair descent, and 3 trials of a 5-metre self-paced walk.	Integration: IMU and Vicon Location and Ease: Wearable sensor were attached to the lower limbs with double-sided hypoallergenic tape
7	Using Knee Acoustical Emissions for Sensing Joint Health in Patients with Juvenile Idiopathic Arthritis: A Pilot Study	No.1 sensor on the knee placement-Right and left Knee	uniaxial analog accelerometer	Knee audio score	Integration: The signals from the accelerometer were recorded using a data acquisition module (USB-4432, National Instruments Corporation, Austin, TX).The recorded signals were analyzed using Matlab (MathWorks, Natick, MA) and Python (Python Software Foundation) Location and Ease: Miniature size accelerometer wrapped in MEDca adhesive tape to ensure strong contact with the medial patellar region.
8	Wearable Sensor-Based Rehabilitation Exercise Assessment for Knee Osteoarthritis	No.3 trunk, thigh and shank placement-Chest , thigh(close to knee) and shank (close to ankle)	opal systems accelerometer and gyroscope magnetometer is not used as it can easily suffer interference from the environment	Angle parameters Shank terminal angle (SAE) Knee joint initial flexion angle (SAE) Thigh raising angle (SLR) Trunk bent forward angle (QSM) Squat angle (QSM) Knee flexion angle (SLR) Hip external rotation angle (SLR)	Integration: Opal system and goniometers used for analysis.The access point receives signal of accelerometers wirelessly from the sensor nodes and transmits those raw data to the workstation through a USB connection. Finally, the accelerations are processed on the working station using MATLAB. Location and Ease: Each wearable sensor is 48.5 × 36.5 × 13.5 mm, weighs 22 grams, Three opal sensors mounted on chest, thigh and shank.
9	Reliability of gait analysis using wearable sensors in patients with knee	No. 4 back, thigh, shank and feet placement-low back , thigh , shank	inertial sensors (iNEMO inertial module), accelerometer and gyroscope	Gait cycle analysis ,RMS of linear accelerations	

	osteoarthritis	and foot			
10	Smart Sensing System for Combined Activity Classification and Estimation of Knee Range of Motion	No.1above the knee placemet- knee, back pocket of leggings	conductive flexible polymeric material The conductivity is provided by the presence of graphitized carbon black nanopowder particles (<500 nm) in a polyurethane substrate.	Gait analysis (walking , running , going up and down the stairs)	Integration: Sensor - Bluetooth connection was established with a notebook (HP Mini 5103 Notebook PC, Hewlett-Packard Company, Palo Alto, CA, USA) for data acquisition. Location and Ease: Wearable smart leggings.
11	Wearable sensors to predict improvement following an exercise intervention in patients with knee osteoarthritis	4- back, thigh, shank, foot placement - Dorsum of the foot shank at the midpoint between the lateral knee joint line and the lateral malleolus thigh at the midpoint between the greater trochanter and the lateral knee joint line.	iNEMO inertial module accelerometer and gyroscope accelerometer data is only used	6 week hip strengthening exercise taking KOOS (Knee Injury and Osteoarthritis Outcome Score) subscale score	Integration: 4 inemo Inertial unit , data analysis in Matlab Location and Ease: 4 units placed on Lower back , thigh,foot and shank, wired connection between the 4 sensors.
12	A Machine Learning and Wearable Sensor Based Approach to Estimate External Knee Flexion and Adduction Moments During Various Locomotion Tasks	2- thigh and shank Placement- The patch pockets at the upper and lower frontal end of the knee sleeve.	IMU(accelerometer and gyroscope)	Artificial neural network (ANN) that estimates external knee flexion moments (KFM) and external knee adduction moments (KAM) during various locomotion tasks	Integration : IMU sensor along with Full body kinematics and GRFs (1,000 Hz, AMTI Inc.,Watertown, MA) were collected synchronously using a marker-based motion capture system Location and Ease : Knee Sleeve , The two inertial measurement units were placed in the patch pockets at the upper and lower frontal end of the knee sleeve.
13	A wearable system for knee flexion/extension monitoring: design and assessment	1-above the knee Placement- knee band and in next setting the sensor was placed 5 cm above knee	fiber Bragg grating (FBG)	the wearable system is capable of monitoring knee movements during walking and quickly identifies the number of stance and swing phases of the gait	Integration: FBG sensor data is fed to pc (analysis in Matlab) and integrated to 3D camera. Location and Ease: The FBG sensor embedded in the silicone brick and anchored on the knee brace.

				at different speeds.	
14	TracKnee: Knee Angle Measurement Using Stretchable Conductive Fabric Sensors	1- sleeve above the knee Placement- knee angle measurement (knee extension and flexion)	3 model tech First, a model is created to determine knee angles from the shift in the front of the knee's length. Next, create an Ordinary Least Squares (OLS) regression model to calculate knee angles using height and the change in length across the front of the knee. Second, a model is created to estimate the change in conductive fabric length based on the resistance of the fabric. In an experiment, we repeatedly stretched our conductive cloth to predetermined lengths while measuring the resistance at each of them. We then used a third-degree polynomial regression to model this data. Third, we used a voltage divider to model voltage to our fabric's resistance.. Overall, using these models allowed us to measure knee angles using our stretchable conductive fabric. material used: Eonyx Conductive Stretchable Fabric	knee angle measurement (knee extension and flexion)	Integration: Sensors and other electronic components embedded to Knee sleeve,along with a Medi Gauge digital goniometer and a fabric tape measure to collect statistics on each participant's knee. Android application and Google pixel 2 is integrated with the device. Location and Ease: The knee sleeve is wrapped around the knee and wireless technology - Bluetooth is used
15	Sleeve for Knee Angle Monitoring: An IMU-POF Sensor Fusion System	1- knee sleeve consisting of 2 IMUs and 1 polymer optical fiber (POF) Placement- pelvis, thigh, leg and foot for both sides	The system consists of merging data from two IMUs and one intensity variation-based POF curvature sensor using a quaternion-based Multiplicative Extended Kalman Filter (MEKF) no assumption about IMU sensors mounting has been made POF- a sensitive zone is created principle variable- accelerometer. Gyroscope is used to differentiate gait stages	Gait analysis (walking) , gait cycle,knee angle(flexion and extension)	Integration: IMU-POF fusion Location and Ease: two 3D printed sensor enclosures integrated into a commercial 3-adjustments neoprene knee sleeve via Velcro and elastic straps.

16	A Novel Flexible Wearable Sensor for Estimating Joint-Angles	1- The sensing unit is kept on the thigh and the end of the string is stuck to the shank. Placement- Thigh and shank	a retractable string sensor and guidance tubes. The retractable string sensor (AndyMark Inc., IN,USA [24]) contains a retractable reel (steel wire), a string, and a potentiometer that measures the amount of rotations of the reel; The string was aligned by the guidance tubes that were sewn on the fabric such that the string did not deviate from its position and trajectory.	Joint angle estimation (knee angle-RMSE)	Integration: integrated system that combines the sensing unit, 9 axis inertial movement units (IMU), a wireless transmission module, an internal memory (micro SD card) module, and a microcontroller. Location and Ease: The retractable string sensor was aligned by the guidance tubes that were sewn on the fabric such that the string did not deviate from its position and trajectory.The wearable system was placed on thigh and shank
17	Use of wearable technology for performance assessment: A validation study	3 2- IMU 1- a flexible sensor [attachable wearable system (AWS)] Placement- waist and thigh pocket	System 1- . The AWS comprises a flexible sensor unit sewed into a tight-fitting trouser garment and positioned over the lateral aspect of the right knee. The positioning was adjusted to fit each subject’s underlying knee anatomy. A change in resistance occurs every time a force is exerted on the material. Based on this principle, the AWS can be used to detect and sense knee motion system 2- an IMU system with a 3-axis accelerometer and 3-axis gyroscope. Data output from the AWS was acquired system 3- waist-worn OpalTM IMU principal variable- accelerometer	Descriptive statistics (mean (SD)) to analyse results,measuring FTSST duration,stride time and stride length, values were compared to the relative reference parameters.	Integration: Portable Sensor +AWS system +Bluetooth module.AWS. Data was transmitted to a laptop (HP EliteBook, Hewlett-Packard Company, Palo Alto,CA, USA) and acquired via a customised C++ interface. Location and Ease: Sensing system as well as markers attached on the right greater trochanter (RGT) and right posterior iliac spine (RPSIS).Many tapes and wires attached.
18	Remote Gait Analysis Using Wearable Sensors Detects Asymmetric Gait Patterns in Patients Recovering from ACL Reconstruction	1- rectus femoris of each leg	Accelerometer and sEMG	Gait analysis (walking), stride length and stride cycle analysis	Integration : Sensor data were collected and analysed in Matlab platform Location and Ease: Single wearable sensor and sEMG on each leg (rectus femoris)
19	Gait posture estimation using wearable acceleration and gyro sensors	4(thigh and shank of each leg) Placement- lower limb (both thighs and shanks)	tri-axial acceleration sensor and three single axis gyro sensors	Angular velocity measurement (hip adduction abduction angle , knee flexion-extension angle measurements)	Integration: Sensors +Motion capturing reference camera Location and Ease: Sensor units are small but placed in multiple locationsSensor units are placed on four body segments, on both thighs and both shanks (RT, LT, RS, and LS).

20	A Preliminary Test of Measurement of Joint Angles and Stride Length with Wireless Inertial Sensors for Wearable Gait Evaluation System	7 Placement- thigh , shank and foot	each sensor consists of 3-axis accelerometer, a 2-axis gyroscope, and a 1-axis gyroscope In this study, considering practical use, Kalman filter-based joint angle estimation of lower limbs without calibration, and resetting during measurement were proposed and tested	Joint angle measurement of lower limb , stride length analysis	Integration : Wireless Sensor+Portable PC Location and Ease:Wearable sensors are attached on the feet, the shanks and the thighs of both legs, and the lumbar region. Wireless technology- Bluetooth
21	Ambulatory Estimation of Knee-Joint Kinematics in Anatomical Coordinate System Using Accelerometers and Magnetometers	4 accelerometers and magnetometers. 2 sets of sensors. each set consisted of 1. two MAG(inertial measurement unit) 2. two MM2860 (triaxial accelerometers) Conc: 4 groups of accelerometer values and 2 groups of magnetometer values	Accelerometers: 2 groups of accelerometer data were obtained from one sensor set. A resultant accelerometer reading was obtained using a physical-sensor-difference based algorithm on these 2 groups in order to eliminate various errors(translational acc, artifacts etc.). The resultant reading represents the reading of a virtual sensor placed on the knee joint. A similar procedure is followed for the other sensor set. The virtual sensors overlap and hence are different in their orientation would represent the orientation of the 2 sensor groups(leg segments). The rotation matrix is found using a virtual-sensor difference-based algorithm and this would present the ROM. Magnetometers: a similar approach but uses only virtual-sensor difference-based algorithm the devices where attached on lateral side, on one of the two-step slides of a stainless steel telescopic slide rail reference system- A commercial optical motion analysis system, NAC Hi-Dcam II digital high-speed camera systems Without integration of angular acceleration or angular velocity for 3-D lower limb joint kinematic analysis, the calculated result is not distorted by offset and drift.	The flexion/extension (f/e), abduction/adduction (a/a), and inversion/extension (i/e) rotation angles of the knee joint in the anatomical joint coordinate system were estimated.	Integration :The proposed wearable sensor system mainly comprised one piece of MCU (H8/3694, from Renesas Technology Corporation), two triaxial accelerometers (MM-2860 Sunhayato, Japan), and two MAG3 s (MEMSense,MAG10–1200S050, analog inertial sensor consisting of a triaxial magnetometer, an accelerometer and a gyroscope, ±1200◦/s, ±10 g, ±1.9 G). The MCU was used to capture accelerations and magnetic field data from the sensors, store data in the EEP-ROM real time, and communicate with a PC after each test. Also has an Optical Motion system for capturing motions. Location and Ease: Entire thigh and shank the wearable system is placed , lots of wired connections.

22	A new ambulatory system for comparative evaluation of the three-dimensional knee kinematics, applied to anterior cruciate ligament injuries	2(thigh and shank)	Each module contained three gyroscopes (angular velocity)	Knee angle measurement, ROM (flexion–extension, internal–external rotation, and abduction–adduction)	Integration: Sensor+Physilog data logger Data analysis in Matlab Location and Ease:The proposed system composed of two 3D gyroscopes fixed on the thigh and on the shank with silicone straps

IV. DATA SYNTHESIS

The goal of this study was to analyse all wearable technologies currently available that aid in knee health monitoring in the most practical way and to determine whether or not their output parameters are pertinent to therapeutic treatments. Based on these factors, we conducted the study using five themes: the wearable sensor's technology, the study population, where the sensor was placed on the patient, the clinical relevance of the outcome parameter, and the technology's accessibility.

➢ *Sensor Technology*

In order to examine the uses of wearable sensor technology for clinically meaningful outcome measures for different knee disease situations such osteoarthritis and ligament tear, extensive research and literature analysis were carried out for 22 papers. The Inertial Measurement Unit (IMU) was extensively used by several researchers. SHIMMER 2R unit consisting of a triaxial accelerometer, gyroscope, and magnetometer was embedded to elastic therapeutic tape for gait analysis and to measure the knee velocity angles and knee velocity curves[1].Inertial sensors equipped with tri-axial accelerometers, gyroscopes, and magnetometers are used for collecting data, out of which the gyroscope plays a major role in collecting thigh angular velocities. Moreover, in articles [2-6,18-20], the IMU sensors were used for collecting acceleration and angular velocities for different exercises like knee extension-flexion, hip abduction, hip flexion-extension, etc. Comparative analysis was conducted between the wearable Shimmer sensor (consists of 5 shimmer 2r's and an inbuilt 3-axis MEMS accelerometer) and the Samsung galaxy note smartphone which has inbuilt K3DH acceleration & K3G gyroscope sensors in article[3]. The biometric system parameters such as Equal Error rate (EER) and Genuine Reject rate (GRR) were calculated for the aforementioned sensor techniques to analyze the individuals' gait pattern and systems' ability to recognize an individual's gait. A commercially available IMU sensor called Opal sensor was used by some researchers[5-6,8,17]for the assessment of gait and balance to help clinicians and researchers in interpreting, collecting, and storing the gait data. The system comprised wireless and wearable inertial sensors with each inertial sensor having a 3-axis14 bits accelerometer, a 3-axis 16 bits gyroscope, and a 3-axis16 bits magnetometer to study parameters such as stride length, stride velocity, knee Range of Motion (ROM), and knee angle.

The features of knee acoustics accelerometer are broad bandwidth ranging from 2Hz-10kHz, high sensitivity of 100 mV/g, low noise floor (700µgrms), and low weight of about 1 gram[7].The the iNemo inertial module which has four synchronized inertial sensors with a sampling rate of 100 Hz and acceleration range of ±16 g[8-9]. Textile-based Smart leggings that have conductive flexible polymer as the sensing unit integrated into them. The black carbon nano-tube powder provides conductivity to the polymer allowing it to sense the knee motion during flexion-extension movement[10]. In recent years, the wearable system-based Fiber Bragg Grating (FBG) has been used to monitor knee movements due to its small size and flexibility. FBG is housed into a silicone brick and has two flexible sensors within the system that get strained or compressed during knee flexion-extension movements[13]. A novel fabricated TracKnee wireless sensing system has been developed to monitor and record the knee angles. The fabricated system has a soft stretchable conductive polymer which is washable by just removing the non-washable electronic components embedded to it[14].

Some studies have implemented a system by combining the data from two IMUs and Polymer Optical Fiber (POF) curvature sensors[15]. The fusion of the IMU-POF sensor system helps in estimating the knee flexion-extension angles accurately and faster. Furthermore, the fusion system is free of Magnetometer and therefore it can be utilized indoors for monitoring the knee angles. Yet another, flexible wearable sensor consisting of a reel, potentiometer, and string to measure the joint angles by the amount of skin stretch during the joint movements[16].som research conducted assessment of the gait conditions by deploying three portable sensors which include an attachable wearable system (AWS), and two IMUs. AWS system senses the knee motion when a force is exerted on the composite material of the system and the resistance is changed. The wearable wireless sensor system comprises of 3-axis accelerometer, a 2-axis gyroscope, and a 1-axis gyroscope to estimate the stride patterns, acceleration, and angular velocities of the subjects[21].

- *Reviewer Observations*

Majority of the research articles have analyzed knee gait parameters such as knee velocity, knee range of motion knee joint angle estimation, abduction-adduction angle of hip extension-flexion angle of the knee, thigh-shank angular velocity, stride length, and stride velocity as the outcome measures. The preferred sensor for this purpose was an IMU. The Shimmer 2R module appears to be suitable for measuring meaningful gait parameters regarding knee angles, velocities, force limits, and is capable of overcoming the shortcomings of stationary gait laboratories[1]. The cost-effective wearable IMU unit has been effective in determining the thigh angular velocities for the ACLR population and has exhibited high sensitivity of about 81% and specificity of 100% according to research. The novel knee acoustics system designed is cost-effective for monitoring patients suffering from JIA[7]. Furthermore, the knee audio scores recorded by the system can be utilized for assessing treatment efficacy. some researches have proposed a system that is a combination of the IMU module and surface Electromyography (EMG), it has potentially identified the gait asymmetries between the affected and unaffected legs of the patients who underwent surgical reconstruction of their ACL when comparing the walking speeds before 6 weeks of surgery and after 14 weeks of surgery[18].

- *Sensor Placement*

After analysing many articles we mainly focus on the knee gait patterns for different individuals with different health conditions, therefore the majority of the sensors discussed in the sensor technology section were placed on the lower body. Thigh and Shank were the common locations for wearable sensor placement followed by the knee. According to research studied the sensors were placed in the thigh and shank region. Kinematics and kinetics measured for most of the research works were about the anterior thigh, mid-lateral thighs, and shank close to the ankle region[1-2,8-9,15-16,18-20,22].

Three shimmer 2R units were used in which the first sensor was dorsally placed on the lumbosacral junction, the second sensor on the iliotibial band about 20 cm cranial of the knee joint gap, and the third sensor was placed at the medial aspect on the tibial about 20 cm caudal of the knee joint gap[1]. The orientation of the IMU Sensors were places at X-axis aligned superior- inferiorly with the greater trochanter and lateral epicondyle of the femur, bilaterally[2]. The three opal sensors were aligned well to the long axis of the body segment[8].

Shimmer module and galaxy note smartphone sensors used in were placed on the Leg, Hand wrist, pant pocket, shirt pocket, and bag (left and right side) to study the gait patterns[3]. Apart from this, IMU sensors utilized in some of the studies were placed on the patch pockets at the upper and lower frontal end of the knee sleeve and the thigh and waist pockets[12,17]. According to few studies the sensors were fixed closely to the knee region[5-7,10-11,13-14,21]

- *Population*

Most of the study conducted on healthy population with no musculoskeletal pathologies, no gait abnormalities, and no knee injuries[19-21]. Gait analysis of knee was performed on the patients who had undergone knee arthroplasty suffering from primary osteoarthritis and the patients with no knee surgical history but having osteoarthritis[9,11]. Some experiments includes subjects who had undergone surgical reconstruction of their anterior cruciate ligament (ACL)[2,18], while some studies performed the testing on men deficient of unilateral ACL[22]. The study was conducted to estimate the knee flexion-extension angles performed testing on 13 males exhibiting bowlegs with a minimum inter-knee distance of 0.05 m[12]. The table below displays the patient demographics of the 22 research articles taken for study.

Table 3 The Patient Demographics of the 22 Research Articles Taken For Study

Research Paper No.	Total Number of Subjects	Age Range	Weight	Height	Body Mass Index (BMI)
[1]	6 (3 men and 3 women)	52-68	-	-	22.7-29.4
[2]	21 (12 men and 9 women)	28.8±11.2	69.7±13.1kg	170.9±9.9 cm	-
[3]	73 (53 men and 20 women)	14 -52	50-107kg	150-193cm	-
[4]	35	20-85	-	-	-
[5]	30 (20 M and 10 F)	43.40 ± 9.45*(H) 69.05 ± 11.18*(P)	73.25 ± 13.04*(H) 77.85 ± 12.00*(P)	171.80 ± 7.81*(H) 170.05 ± 7.49*(P)	24.73 ± 3.58*(H) 28.81 ± 3.05*(P)

[6]	17		-	-	BMI >30 kg/m^2
[7]	8 (2 men and 3 female)	14.7±2.1	48.9±3.6 kg	157.1±10 cm	-
[8]	10(5 men and 5 women)	-	56 ± 10.11 kg	163.9 ± 8.9 cm	-
[9]	10	≥40 years of age	-	-	≤35 kg/m^2
[10]	12	27 ± 5	66 ± 12 kg	1.7 ± 0.1 m	-
[11]	39	≥40 years of age	-	-	≤35 kg/m^2
[12]	13 men	26.1 ± 2.9	78.4 ± 5.9 kg	178.7 ± 5.5 cm	-
[13]	1 man	28 years	85 kg	179 cm	-
[14]	6 (3 men and 3 women)	18-35	-	4’11”- 6’0”	-
[15]	12 men	23.08 ± 2.31	71.32 ± 9.91 kg,	1.72 ± 0.05 m;	24.03 ± 2.89 kg/m^2
[16]	9	18-80	-	-	-
[17]	14 (7 men and 7 women)	Mean age 25	Mean weight 68.1 kg	Mean height 1.71m	-
[18]	8	26.6 ± 9.1	-	-	-
[19]	3 men	23-28	56-73 kg	170-180cm	-
[20]	3 men	22-23	-	-	-
[21]	5 (4 men , 1 women)	25 ± 3	170 ± 5	60 ± 11 kg	-
[22]	5 men	19-39	-	-	-

- *Clinical Relevance*

In order to analyze the clinically relevant measures of experiments conducted by 22 research articles, we have taken outcome measures, testing time, and minimum detectable changes parameters into consideration. The parameters such as knee velocity, acceleration measurements, knee joint angle estimation, abduction-adduction angle of hip extension-flexion angle of the knee, and thigh-shank angular velocity were measured by researchers. The experiments performed by the articles have considered stride length, stride velocity, stride velocity, number of swing, and stance phase as the outcome measures.

Table 4 Clinical Relevance

Research Article Number	Testing Time
[1]	30 minutes of continuous recording per patient and session
[3]	The total data collection time for each individual is approximately 4.5 minutes.
[6]	5 mins of self-walk
[9],[11]	Each subject walked on a Treadmill for 3-5 minutes
[17]	For each trial data was collected for 40 seconds

[18]	Each subject's daily life activities were recorded for 15.3 ± 5.4 hours per day
[20]	Subjects walked on a treadmill for 90 seconds
[22]	Patients performed sports activities several times per week

The experiment was conducted before knee arthroplasty surgery and 12 months post-surgery, it was noticed that five patients had shown significant improvement in their knee functions except for one who didn't benefit and had anteroposterior instability in the knee[1]. Gait analysis research were observed through ANOVA Test that patients who underwent hip or knee replacement surgery have a statistically significant positive impact on the spatiotemporal parameters[5]. The knee audio scores recorded for JIA patients before and after treatment, the scores decreased from 0.89±0.012 to 0.25±0.20[7]. IN the experiment conducted on five men suffering from ACL, it was observed that after one year of surgery four patients were classified normal and one almost normal. The changes in the kinematics of the five patients were noted which states that they had lower flexion-extension ROM and higher internal-external rotation ROM in comparison with the contralateral knee and the 3D kinematics was changed after an ACL lesion and remained altered one year after the surgery[7].

- *Accessibility*

To understand and study the accessibility of the wearable devices and systems proposed by the 22 research articles parameters such as integration and ease of the wearable devices were taken into account. Almost all the wearable sensors proposed by the research articles were integrated with Bluetooth technology for transmission of the data or signal captured by the sensors and were connected to computers/pcs/laptops. The sensor data and signals collected in an research study were analyzed and processed in the MATLAB platform [2,7,9,11,18,22]and some studies use the Java platform for analyzing the sensor data[1].An android application was used to study the sensor data[5]. The wearable sensing system utilized by the majority of the research articles was comfortable and had wireless communication technology. The sensor and the electronic components were embedded in flexible fabric or textile and subjects did not report any dermal irritation. The majority of the wearable sensors were secured firmly either using therapeutic tape, Velcro straps, double-sided adhesive tapes, elastic straps, knee sleeves, and silicone straps.

V. CONCLUSION

The current analysis demonstrates that IMUs provide adequate precision to supplement, combine, and widen the scope of rehabilitative equipment already available. By examining outcomes that would traditionally be quantified separately, such as ROM, gait analysis, and the detection of asymmetric knee loading, IMUs can combine different rehabilitation metrics while also introducing new rehabilitative markers, like the quantification of instability. In the population undergoing knee surgery, IMUs can take the place of time-consuming devices like motion-capture systems and force platforms. This paper describes about the researches that were carried too put forth the use of wearable technologies for knee rehabilitations along with gait analysis. The use of technology into rehabilitation along with assessment and an diagnostic tool was studied. The aim was to study the use of technology in health individuals, pre and post operative condition as well as some of the musculoskeletal injurie. The support provided by various emerging technologies for accurate monitoring of orthopedic motions, physiotherapy, and rehabilitation is highlighted in this study. It also discusses how the patient's adequate participation is necessary to achieve the best functional results. In order to find out an smart rehabilitative tool that allows an accurate monitoring and evaluation of the customized exercises. The current study provides the initial framework for human join motion estimation and tracking using inertial sensing node. The relevant articles were studied to orient an estimated algorithm that can be design to fit knee joint and its activities. This report has detailed data of ongoing experiment using a wearable sensors to record data which clarifies how sensors can be utilized to assess the rehabilitation status of patients with leg injuries. This study helps to understand that how technology with wearable sensors are helpful in improving the accuracy of the predictions. Conclusions from numerous studies imply that M/IMUs are a suitable substitute for motion-capture based systems when studying human motions.

REFERENCES

[1]. Clinical Evaluation of a Mobile Sensor-Based Gait Analysis,Method for Outcome Measurement after Knee Arthroplasty (2014)
[2]. Detection of Knee Power Deficits following ACL Reconstruction Using Wearable Sensors (2018)
[3]. Biometric Database for Human Gait Recognition using Wearable Sensors and a Smartphone (2017)
[4]. Monitoring and Assessment of Rehabilitation Progress on Range of Motion After Total Knee Replacement by Sensor-Based System (2020)
[5]. Concurrent validity and inter trial reliability of a single inertial measurement unit for spatial-temporal gait parameter analysis in patients with recent total hip or total knee arthroplasty (2020)
[6]. Predicting Knee Joint Kinematics from Wearable Sensor Data in People with Knee Osteoarthritis and Clinical Considerations for Future Machine Learning Models (2022)
[7]. Using Knee Acoustical Emissions for Sensing Joint Health in Patients with Juvenile Idiopathic Arthritis: A Pilot Study (2018)
[8]. Wearable Sensor-Based Rehabilitation Exercise Assessment for Knee Osteoarthritis (2015)

[9]. Reliability of gait analysis using wearable sensors in patients with knee osteoarthritis (2016)
[10]. Smart Sensing System for Combined Activity Classification and Estimation of Knee Range of Motion (2015)
[11]. Wearable sensors to predict improvement following an exercise intervention in patients with knee osteoarthritis (2017)
[12]. A Machine Learning and Wearable Sensor Based Approach to Estimate External Knee Flexion and Adduction Moments During Various Locomotion Tasks (2020)
[13]. A wearable system for knee flexion/extension monitoring: design and assessment (2020)
[14]. TracKnee: Knee Angle Measurement Using Stretchable Conductive Fabric Sensors (2019)
[15]. Sleeve for Knee Angle Monitoring: An IMU-POF Sensor Fusion System (2019)
[16]. A Novel Flexible Wearable Sensor for Estimating Joint-Angles (2016)
[17]. Use of wearable technology for performance assessment: A validation study
[18]. Remote Gait Analysis Using Wearable Sensors Detects Asymmetric Gait Patterns in Patients Recovering from ACLReconstruction (2015)
[19]. Gait posture estimation using wearable acceleration and gyro sensors
[20]. A Preliminary Test of Measurement of Joint Angles and Stride Length with Wireless Inertial Sensors for Wearable Gait Evaluation System
[21]. Ambulatory Estimation of Knee-Joint Kinematics in Anatomical Coordinate System Using Accelerometers and Magnetometers
[22]. A new ambulatory system for comparative evaluation of the three-dimensional knee kinematics, applied to anterior cruciate ligament injuries
[23]. Kubakaddi, S., Ravikumar, K., & DG, H. (2013). Measurement of cartilage thickness for early detection of knee osteoarthritis (KOA). 2013 IEEE Point-of-Care Healthcare Technologies (PHT). doi:10.1109/pht.2013.6461321
[24]. Rameshkumar, R., Sharan, D., & Ajeesh, P. S. (2010). Description and Outcome of Treatment of a New Triad of Anterolateral Knee Pain and Movement Dysfunction. 6th World Congress of Biomechanics (WCB 2010). August 1-6, 2010 Singapore, 977–980. doi:10.1007/978-3-642-14515-5_249
[25]. Oberländer, K. D., Karamanidis, K., Höher, J., & Brüggemann, G.-P. (2011). Evidence of Feedforward Postural Adjustments to Reduce Knee Joint Loading in ACL Deficient Patients at Cost of Dynamic Stability Control. 15th Nordic-Baltic Conference on Biomedical Engineering and Medical Physics (NBC 2011), 264–267. doi:10.1007/978-3-642-21683-1_67
[26]. Quantified self and human movement: A review on the clinical impact of wearable sensing and feedback for gait analysis and intervention
[27]. Henriksen M, Graven-Nielsen T, Aaboe J, Andriacchi TP, Bliddal H: Gait changes in patients with knee osteoarthritis are replicated by experimental knee pain. Arthritis Care Res 62:501-509, 2010
[28]. Hodges PW, Mellor R, Crossley K, Bennell K: Pain induced by injection of hypertonic saline into the infrapatellar fat pad and effect on coordination of the quadriceps muscles. Arthritis Rheum 61:70-77, 2009
[29]. Tucker KJ, Hodges PW: Motoneurone recruitment is altered with pain induced in non-muscular tissue. Pain 141: 151-155, 2008
[30]. Nonsurgical Management of Knee Pain in Adults BRANDON Q. JONES, MD; CARLTON J. COVEY, MD; and MARVIN H. SINEATH, JR., MD Nellis Family Medicine Residency, Nellis Air Force Base, Nevada
[31]. A review of wearable sensors and systems with application in rehabilitation Shyamal Patel1,2, Hyung Park3 , Paolo Bonato1,4, Leighton Chan3 and Mary Rodgers5,6*
[32]. Smart wearable body sensors for patient self-assessment and monitoring Geoff Appelboom1*, Elvis Camacho1 , Mickey E Abraham1, Samuel S Bruce2, Emmanuel LP Dumont2, Brad E Zacharia, Randy D'Amico3, Justin Slomian4, Jean Yves Reginster4, Olivier Bruyère4 and E Sander Connolly Jr1
[33]. Barriers to treatment adherence in physiotherapy outpatient clinics: A systematic review Kirsten Jack a , Sionnadh Mairi McLean b,*, Jennifer Klaber Moffett c , Eric Gardiner c
[34]. Rose MJ, Costello KE, Eigenbrot S, Torabian K, Kumar D. Inertial measurement units and application for remote health care in hip and knee osteoarthritis: Narrative review. JMIR Rehabilitation and Assistive Technologies. 2022 Jun 2;9(2):e33521.
[35]. Prill R, Walter M, Królikowska A, Becker R. A systematic review of diagnostic accuracy and clinical applications of wearable movement sensors for knee joint rehabilitation. Sensors. 2021 Dec 9;21(24):8221.