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Development and Validation of the Motion Shirt: A Wearable Sensor System for Monitoring Upper Limb Motion in Shoulder Joint Replacement Patients

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Abstract

Wearable sensors have become the study topic of researchers across various clinical disciplines, presenting promising avenues for their integration into clinical practices. Inertial measurement units (IMUs) have become significantly notable among the variety of sensor types, due to their non-invasive, and lightweight design. Moreover, they are increasingly used and applied in novel motion technologies since IMUs collect precise motion and orientation data when attached to specified body regions. In this dissertation, a wearable sensor system known as the Motion Shirt, equipped with 5 IMU sensors, previously developed and embedded into a flexible garment, is used to assess psychometric properties arms and shoulders motion data.

A rigorous validation study has been conducted to investigate the efficacy and reliability of the Motion Shirt. A cohort of patients on the waitlist of shoulder joint replacement (SJR) surgery were recruited and their motion performance in a standard test, the Functional Impairment Test-Hand and Neck/Shoulder/Arm (FIT-HaNSA) were compared against the Dartfish Motion Analyzer, a widely utilized tool in motion analysis. The Motion Shirt's validity was revealed through this comprehensive test and its accuracy was also studied across different tasks of the FIT-HaNSA and participants' performances.

Reliability of the Motion Shirt was assessed in another study by evaluating the intraclass correlation coefficient of collected arcs of motions in similar cohort of patients on the waitlist of SJR surgery during the FIT-HaNSA test. A moderate to excellent reliability was achieved in all three tasks of the FIT-HaNSA test across both elevation and plane of elevation axes.

Furthermore, A longitudinal study on a cohort of patients who have undergone SJR surgery was conducted to assess the Motion Shirt's ability in collecting motion outcomes and recovery patterns. After comparing the motion data, it was demonstrated that significant and notable outcomes such as number of moves and promptness were improved, and thus the Motion Shirt further proved its efficacy in recording upper limb motion data over longer periods of data collection.

Wearable sensor applications were not only investigated in clinical contexts, but also were studied through their demonstration in smartphones. In this regard, a systematic review is conducted to assess the smartphone applications on the assessment of range of motion in upper limbs

considering the rising trend of smartphone sensor and photography applications. Routine clinical and rehabilitation practice can significantly improve through the inclusion of wearable sensor systems such as the Motion Shirt as well as smartphone applications. Additionally, patients' quality of life and assessment of health care professionals can be ameliorated via this novel technology. This paradigm shift to remote rehabilitation and monitoring not only improves patient care, but also prepares the door for the creation of novel, patient-centered rehabilitation programs suited to the specific needs of musculoskeletal patients.

Keywords

Wearable Sensor System, Inertial Measurement Unit, Shoulder Joint Replacement Surgery, FIT-HaNSA,

Summary for Lay Audience

Wearable sensors are becoming increasingly important in healthcare research, offering new ways to improve patient care. One type of sensor, the inertial measurement unit (IMU), is particularly useful because it is lightweight and non-invasive. These sensors can accurately track motion and orientation when attached to the body. In my research, I developed a wearable sensor system called the Motion Shirt, which uses five IMU sensors embedded in a flexible garment to monitor arm and shoulder movements continuously and accurately.

To ensure the Motion Shirt works effectively, I conducted several studies. First, I tested its accuracy by comparing it to a widely used motion analysis tool called the Dartfish Motion Analyzer. I recruited patients who were waiting for shoulder joint replacement (SJR) surgery and asked them to perform a standard set of movements. The Motion Shirt proved to be very accurate in tracking their movements.

Next, I assessed the reliability of the Motion Shirt by checking how consistently it measured movements over time. I found that the Motion Shirt had moderate to excellent reliability in all tasks, meaning it provided consistent and dependable data.

Additionally, I conducted a long-term study with patients who had already undergone SJR surgery. This study showed that the Motion Shirt could effectively track their recovery progress, providing valuable information about improvements in their movement and responsiveness over time.

Beyond the Motion Shirt, I also reviewed how wearable sensors, including those in smartphones, can be used in clinical settings. These technologies can greatly enhance routine clinical and rehabilitation practices, making them more efficient and personalized. By enabling remote monitoring and rehabilitation, these sensors can improve patient care and quality of life.

In summary, the Motion Shirt and similar wearable sensor technologies have the potential to revolutionize healthcare by providing accurate, reliable, and long-term monitoring of patients' movements, ultimately leading to better outcomes and more tailored rehabilitation programs.

Co-Authorship Statement

The core idea of the research question and the design of the studies were developed by Sohrob Milani Zadeh and his supervisor, Dr. Joy C MacDermid. The committee members were then provided their feedback on the main idea, the details of each milestone, and their expectations.

Co-authors were invited when additional help and expertise were required. The specific contributions of each co-author are presented below:

Chapter 1: **Introduction**

Sohrob Milani Zadeh– Sole Author

Chapter 2: Assessing the Validity of a Wearable Shoulder Motion Tracking System Through Comparison with Dartfish in Patients Undergoing SJR Surgery

Sohrob Milani Zadeh: Primary author, study design, participant recruitment, running data collection process, data analysis, writing manuscript, preparing the manuscript for submission.

Joy MacDermid: Co-author, conception of study idea and study design, revising the manuscript for important intellectual content, final approval of the manuscript before submission.

G Daniel Langohr: Co-author, manuscript reviewer

James Johnson: Co-author, manuscript reviewer

Chapter 3: Assessing the Inter-trial reliability of the Shoulder Range of Motion Measurement Using a Wearable Motion Tracking System, "Motion Shirt"

Sohrob Milani Zadeh: Primary author, study design, participant recruitment, running data collection process, data analysis, writing manuscript, preparing the manuscript for submission.

Joy MacDermid: Co-author, conception of study idea and study design, revising the manuscript for important intellectual content, final approval of the manuscript before submission.

G Daniel Langohr: Co-author, manuscript reviewer

James Johnson: Co-author, manuscript reviewer

George S Athwal: Co-author, manuscript reviewer

Kenneth J. Faber: Co-author, manuscript reviewer

Chapter 4: Assessment of Shoulder Joint Replacement Patients' Motion Outcomes Using a Wearable Sensor System, Motion Shirt: A Six-Month Post-Surgery Evaluation

Sohrob Milani Zadeh: Primary author, study design, participant recruitment, running data collection process, data analysis, writing manuscript, preparing the manuscript for submission.

Joy MacDermid: Co-author, conception of study idea and study design, revising the manuscript for important intellectual content, final approval of the manuscript before submission.

G Daniel Langohr: Co-author, manuscript reviewer

James Johnson: Co-author, manuscript reviewer

George S Athwal: Co-author, manuscript reviewer

Kenneth J. Faber: Co-author, manuscript reviewer

Chapter 5: Reliability and validity of using smartphone sensor and photography to measure hand and upper extremity joints range of motion; A systematic review

Sohrob Milani Zadeh: Primary author, study design, running search strategy, study selection, data extraction, quality appraisal, data analysis, writing manuscript, preparing the manuscript for submission.

Joy MacDermid: Co-author, conception of study idea and study design, revising the manuscript for important intellectual content, final approval of the manuscript before submission.

G Daniel Langohr: Co-author, manuscript reviewer

James Johnson: Co-author, manuscript reviewer

Erfan Shafiee: Co-author, second reviewer for quality appraisal, second data extractor, manuscript reviewer

Chapter 6: General discussion and future direction

Sohrob Milani Zadeh: Sole author

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Chapter 1

1 Introduction

1.1 Musculoskeletal conditions

Musculoskeletal (MSK) problems are one of the most common healthcare conditions that require ongoing, reliable, and objective clinical measures or therapy. In this regard, 1.71 billion individuals experience musculoskeletal conditions at some point of their lives. MSK conditions are representing the second highest prevalence rate among non-fatal disabilities, contributing to the demand for rehabilitation services [1]. Upper extremity musculoskeletal (UE-MSK) conditions, in particular, are a major concern in today's world because they result in various forms of burden on individuals (such as limited range of movement, feeling pain and discomfort and other forms of limitations), leading to a degradation in quality of life and increased healthcare costs [2]. While an official and reliable global report regarding the prevalence rate of UE-MSK conditions has not been conducted and released (due to the lack of a globally accepted definition of UE-MSK disorders or conditions), a study conducted by Huisstede et al. reported that a high proportion of the MSK disorder population could fall into the UE-MSK category (up to %53 point prevalence rate) [2]. Therefore, clinicians and patients would greatly benefit from improvements in the quality of health assessment, evaluation, and rehabilitation of UE-MSK conditions or disorders. Offering objective, simple, inexpensive, and user-friendly assessment methods can significantly enhance rehabilitation accuracy and diagnostic efficiency while reducing therapy session expenses. On the other hand, recent quarantines and health recommendations imposed by governments and health organizations worldwide in response to the Covid-19 epidemic have dramatically reduced in-person rehabilitation or treatment visits [3].

1.2 Shoulder Joint Anatomy: Glenohumeral Joint

The glenohumeral joint, or the shoulder joint is one of the most mobile joints in the human body, responsible for many complex motions. It is a ball-and-socket joint formed by the articulation of the humeral head (the ball) with the glenoid cavity of the scapula (the socket). A wide range of motions across different axes and planes is allowed by the structure of this joint, including flexion, extension, abduction, adduction, internal and external rotation, and circumduction [4].

The glenoid cavity is a shallow socket, enabling a wide range of movement but also necessitates additional structures to maintain stability. These structures include the labrum (a fibrocartilaginous rim that deepens the socket), the rotator cuff muscles (supraspinatus, infraspinatus, teres minor, and subscapularis), the joint capsule, and the ligaments that surround the joint. All these components provide dynamic and static stability to the glenohumeral joint while enabling the extensive range of motion required for all complex movements [4].

1.3 Shoulder Joint Replacement Surgery

Shoulder joint replacement is a surgical procedure within the field of musculoskeletal conditions. Shoulder joint replacement surgery, also known as shoulder arthroplasty, is a surgical process performed on patients with severe shoulder joint disorders performed to relieve their pain and improve their function. This operation involves replacing the damaged parts of the shoulder joint with artificial components. The increasing global rate of shoulder replacements (up to %235 increase[5]) and the emphasis on improving patient outcomes for joint replacement surgery highlight the importance of shoulder joint replacement in the management of musculoskeletal conditions.

There are several conditions that may necessitate patients to undergo shoulder joint replacement surgery:

1. Osteoarthritis: Osteoarthritis is the most common reason for shoulder joint replacement surgery. It is a degenerative joint disease that causes the cartilage in the shoulder joint to wear away, resulting in pain, stiffness, and limited range of motion [6]. Rotator Cuff Tear Arthropathy, or secondary osteoarthritis occurs when a severe rotator cuff tear leads to the development of arthritis in the shoulder joint. This condition can cause pain, weakness, and limited shoulder function, necessitating joint replacement surgery [7].

2. Rheumatoid Arthritis: Rheumatoid arthritis is an autoimmune disease that causes inflammation in the joints, including the shoulder joint. Over time, this inflammation can lead to joint damage and the need for shoulder joint replacement surgery [8].

3. Avascular Necrosis: Avascular necrosis, also known as osteonecrosis, occurs when the blood supply to the shoulder joint is disrupted, leading to the death of bone tissue. This can result in pain and joint deterioration, requiring shoulder joint replacement surgery [9].

The necessity for shoulder joint replacement surgery is usually determined after a comprehensive evaluation of the patient's symptoms, medical history, and, most critically, physical examination [10]. Medical imaging and other diagnostic procedures may also be applied to identify the amount of joint injury and determine surgery necessity. Some of these diagnostic approaches are as the following:

1. Patient History: The patient's history aims to identify the duration and progression of symptoms considering patient's daily life, previous shoulder injuries or surgeries, and the impact of symptoms on patient's daily activities [10].

2. Physical Examination: A physical examination includes assessing the range of motion (ROM), strength, stability, and tenderness of the shoulder joint. It significantly aids to identify any abnormalities or limitations in shoulder function over a span of different activities [10].

3. Imaging Studies: X-rays, magnetic resonance imaging (MRI), and computed tomography (CT) scans are commonly used to evaluate the current condition of the shoulder joint, identify the level of joint damage and weariness [10].

However, even after a SJR or arthroplasty surgery, there are challenges that weigh heavily against surgical repair outcomes. Even after a successful surgery in restoring cuff integrity, shoulder function remains limited in nearly every case for an approximate six-month duration, and surgical repair must be followed by prolonged rehabilitation therapy, over several months and the results of these interventions are thus different on a case-by-case basis between different patients [11]. Therefore, physical assessments, self-reported questionnaires, and medical imaging processes need to be performed regularly on patients to monitor the patient's shoulder recovery status. The physical assessment sessions usually take place via in-person visits in the clinic prior to the surgery and at several different time points, such as 1 month, 3 months, 6 months, and 12 months after the surgery [12]. The surgeon may ask the patient to perform a certain series of tasks with the purpose of checking the functional abilities that are important to the quality of daily life. However, stability, strength, and ROM assessments are also important evaluations to assess the recovery status of the operated shoulder. Conventional ROM assessments are performed using traditional goniometers and inclinometers [13,14].

1.4 Range of Motion, a critical outcome

The process of ROM assessment includes angle measurements that indicate an individual's ability to move their shoulder joint in different axes and directions. These directions and movements include but are not limited to abduction/adduction, forward flexion/extension, and internal/external rotation [15].

Abduction/Adduction ROM measurement starts with the patient in a seated or standing position while the fulcrum of the goniometer is placed on the center of the shoulder joint in the frontal plane. The patient's arm starting position is by their side, and then they are asked to raise the arm to the maximum level of the side axis parallel to the patient's torso (abduction) and bring it back toward the reverse direction (adduction) in the frontal plane. The goniometer arms are aligned with the acromion process and lateral epicondyle of the humerus, and the indicating values in the end positions will be recorded as ROM in the abduction/adduction direction[15] (Figure 1-1).

Flexion/Extension ROM measurement also starts with the patient in a seated or standing position. Similarly, the goniometer will be placed at the fulcrum of the goniometer over the center of the shoulder joint, and the starting position of the shoulder will be the patient's arm at the side. Then, the patient is asked to raise their arm to the maximum extent in the forward direction, perpendicular to the torso axis (flexion), or in the reverse direction (extension), all in the sagittal plane. The indicated values on the goniometer at the maximum positions will be recorded as the ROM measurement of flexion/extension direction [15] (Figure 1-2).

Internal/External Rotation measurement takes place with the patient in a standing or seated position with the goniometer fulcrum placed on the shoulder joint center. However, the starting position is with the patient's arm by their side, elbow bent at 90 degrees, and forearm pointing forward. Then, the patient is asked to rotate their arm to the maximum level first inward to their torso side (internal rotation) and then outward (external rotation) in the transverse plane. The values will be recorded at the maximum positions as the ROM measurement in this direction. It's important to note that specific techniques and instructions may vary depending on the standardized protocols or guidelines followed [15,16] (Figure 1-3).

Conventional assessment methods of obtaining shoulder ROM, like using goniometers or inclinometers through the previously mentioned processes, are associated with various challenges and issues:

1. The conventional measurement process is time-consuming and laborious, as it requires the presence of usually two clinicians to perform the measurements [17]. Moreover, the goniometer must also be held with both hands, leaving neither hand available for the clinicians to stabilize the body or the proximal region of the joint [18].

2. The measurement is prone to visual errors and subjective influence of clinicians during measurements [17].

3. The shoulder complex includes the glenohumeral, acromioclavicular, sternoclavicular, and scapulothoracic joints (Figure 1-4). Therefore, shoulder joint movement is a complex motion with multiple degrees of freedom, involving different joints such as the glenohumeral joint and the scapulothoracic joint. The coupled motion of those joints results in the most challenging part of human motion to capture [19]. Conventional measurements may not comprehensively capture the full complexity of shoulder motion and may struggle to distinguish specific motions of the shoulder joint, for instance, between glenohumeral and scapulothoracic motions [20].

4. There are reliability and validity concerns regarding traditional measurement methods. Factors such as the patient's positioning and status, soft tissue artifacts during the measurement process, and the clinician's experience in measurement may affect the obtained shoulder ROM value [19].

5. The process of conventional measurements usually includes a limited set of shoulder motions, such as abduction/adduction, flexion/extension, and internal/external rotation, as explained briefly earlier. These motions are performed at a fixed angle and position of the shoulder joint and do not involve more complicated motions at different angles. Therefore, the process may not provide a comprehensive evaluation of the shoulder joint's full range of motion and various functional capabilities [17,20]. Therefore, other axes of motions like

Elevation and Plane of Elevation that capture motion ranges in a spherical coordination might be more informative for daily life activities.

6. Traditional ROM measurement necessitates the patient to assume specific positions and stances, which may involve manual manipulation of the shoulder joint. These positions might not be comfortable nor feasible for all individuals, especially at early time points after the SJR surgery, as patients are often associated with pain, stiffness, or limited mobility, leading to incomplete and inaccurate assessments [19].

7. Typical measurements provide ROM measurements at a single time point, without capturing dynamic and continuous changes in shoulder ROM during daily life and functional activities. Therefore, the lack of a real-time and consecutive monitoring process of shoulder motion might limit the interpretation of the physical assessment, functional abilities, and recovery progress during rehabilitation [19].

8. Although it is important to utilize laboratory equipment to measure shoulder joint kinematics, solely focusing on measurements performed in a laboratory setting will provide limited results and analysis. Therefore, performing the measurement at different settings, especially locations like the patient's home, gives great insight about the rehabilitation process and also aids the surgeon or therapist to devise patient-specific plans and exercises [21].

1.5 Alternative and complementary methods for conventional ROM assessment

Researchers have suggested novel solutions to address the problems or challenges associated with using goniometers, inclinometers, or visual estimations to obtain motion assessments of shoulder joint. Some of these methods are as following:

1. Motion Capture Systems: These systems utilize cameras and 3D motion markers to record the shoulder or other body parts' movements and further analyze it in computer systems to obtain trajectories, orientation, and precise location of joints. Some of these systems use motion markers and some solely rely on the captured images. Image processing techniques are also applied to the recorded videos or images for acquiring a comprehensive data of

motion [22–26]. Motion capture systems offer highly accurate and detailed tracking of movement in three-dimensional space but can be costly and require complex setups with specialized equipment in controlled environments.

2. Electromyography (EMG): EMG systems focus on obtaining the electrical activity of muscles to a nerve's stimulation. The obtained signals are locally specific meaning that for obtaining shoulder muscle activity, sensors need to be placed on the interested parts. EMG signals can assess muscle activation patterns and identify any imbalances or abnormalities in muscle recruitment during motion [27–31]. However, EMG does not provide any information on the position or movement trajectory of the limb.
3. Wearable sensors: Different form of sensors have been introduced and suggested to monitor and track shoulder joint. These sensors vary from inertial measurement units (IMUs), to accelerometers, gyroscopes, and piezoresistive, and strain sensors and are thus utilized for different parts of upper body [27,32–36]. Wearable sensors offer continuous, real-time monitoring of physiological and biomechanical data in natural environments, but they can be limited by battery life, data accuracy, and potential discomfort or interference with daily activities.

1.6 Inertial Measurement Unit

According to the conducted studies and reviews, IMUs are among the most applied type of sensors for tracking upper body motions [27,32,33,35,37–43]. IMU is an electronic system, which is commonly composed of an accelerometer, a gyroscope, and a magnetometer. The accelerometer measures linear accelerations in three dimensions, providing data on how quickly the sensor is moving in space. The gyroscope captures angular velocities, allowing for the tracking of rotational movements in three dimensions. The magnetometer detects magnetic field strength, which helps in determining the sensor's orientation relative to the Earth's magnetic field [44]. These components are crucial as they enable a wearable sensor system to accurately capture and analyze the complex movements of the upper musculoskeletal (MSK) extremities. The accelerometer helps in understanding linear movements, the gyroscope tracks rotational aspects, and the magnetometer ensures precise orientation. Together, they form the basis for providing a comprehensive and reliable motion assessment in real-world scenarios. IMUs are cheap, lightweight, and accurate systems, and can be used for a wide range of applications like sports [45], gaming [46], and health care

[47] (Figure 1-5). The conducted studies have reported IMUs to be more affordable and portable in comparison to motion capture systems, and other motion tracking systems [19]. This advantage makes IMUs suitable for outpatient clinical settings and daily life activities since they can provide a continuous motion measurement that can be also monitored remotely [43]. IMUs can be calibrated in a variety of methods to compensate for drift (the gradual deviation of the IMU's output from the true value due to the accumulation of small errors in the sensors over time) and bias (a consistent offset from the true value that can occur due to imperfections in the sensor's calibration or inherent inaccuracies), which increases the measurement error over time. Regularly resetting the sensor's baseline to recalibrate the orientation and position, and periodic recalibration during use, ensure the sensor's output to remain as accurate as possible over extended periods. IMUs have shown promise in addressing the challenges associated with goniometers and inclinometers in measuring shoulder joint motion [48]. Challenges such as the subjectivity of outcomes, the need for clinician presence during the measurement process, discontinuity, time-consuming measurement processes, and limited measurements to only a set of standardized motions have been sufficiently addressed by wearable sensor applications like IMU-based systems [43].

1.7 Emerging Trends in Wearable Sensor Applications

Several studies focusing on wearable sensors, including IMUs, have been examined. Kim et al. conducted a scoping review study on 43 studies on the uses of wearable sensors for assessing and treating upper extremities (UE) in patients who experienced a stroke [49]. The evaluated studies focused on applications of wearable sensors in obtaining UE functional motion outcomes, identifying motor impairment/activity limitations, and supplementing UE training with various forms of sensor feedback. They concluded that wearable sensors may enhance assessment and treatment beyond traditional clinical procedures by quantifying rehabilitation dose, providing detailed assessments of impairment and activity limitations, tracking daily upper extremity use in real-world settings. Furthermore, this research proved the applicability of wearable sensors, including IMUs, in determining a home-based rehabilitation program, characterizing daily UE usage patterns in patients' daily lives, and evaluating adherence levels to home-based treatment sessions [49].

Maceira-Elvira et al. also conducted a literature review on stroke patients [50]. This study analysis on 24 research papers sought to provide a comprehensive overview of wearable sensor applications

in stroke upper extremity rehabilitation studies from different perspectives. The study evaluated four different categories of IMUs, surface EMG (sEMG) sensors, potentiometers, and flexible sensors in four aspects: diagnostic, recovery/adaptation valuation, extended training, and implementation. The sample sizes of the included studies varied between 3 to 122, and the number of sensors used for data collection varied between 1 to 10. In conclusion, it was established that, in addition to the overall benefits of wearable sensors, IMUs and sEMG sensors provide the best advantages in terms of unobtrusiveness, robustness, usability, and data quality [50].

Another scoping review research conducted by Sethi et al. focused on 25 papers about the application of inertial motion sensors, sEMG-based, and e-textiles-based interactive wearable technologies [29]. This study summarized the existing gaps, limitations, and future use of IMUs and sEMG sensors in various populations, including healthy individuals, stroke patients, and neurologically disabled cohorts of patients. However, limitations associated with applying wearable sensor technologies such as large-sized equipment, time-consuming initial setup procedures, and calibrations have also been discussed. On the other hand, the progress of machine learning techniques and the development of cloud systems have been prospected as a novel solution to solve these problems, making the wearable sensor systems more convenient and efficient [29].

Another scoping review focused on biofeedback designs for home-based rehabilitation applications [51]. In this regard, it was stated that the analyzed feedback presented in the studies was mostly visual, concurrent, and descriptive. Furthermore, the included publications investigated the logic behind the implantation of a feedback system in a wearable system, its usability, and assessments [51].

A systematic review by O'reilly et al. was conducted to evaluate the use of IMU technologies in assessing movement quality in lower limb exercises [52]. The review identified 47 studies that investigated the use of IMU systems for analyzing repetition-based targeted lower limb exercises. The studies were categorized into three categories: exercise detection, movement classification, and measurement validation. Finally, it was concluded that IMU systems are valid and reliable in successfully measuring joint angles and temporal features during lower limb exercises. Although

the study claimed that very few user evaluation studies and clinical trials have been published in this field [52].

1.8 The gap in the knowledge

As IMU sensors become increasingly prevalent in healthcare and clinical settings, the need for a seamless and efficient method of motion assessment grows ever more imperative. Clinical practice requires a continuous, objective, and user-friendly method of motion assessment that also enables clinicians and therapists to remotely monitor patients at different time points, such as pre- and post-surgery durations, while maintaining patient privacy. The proposed solution needs to be validated and tested for accuracy, as the reported outcomes of the system are extremely critical for treatment decisions. Testing conditions need to be standardized for the initial testing phases to ensure that patients' performed motions align with typical standard moves of their daily activities. Moreover, the proposed platform needs to be comfortably integrated into patients' daily lives so it can become part of their ordinary routine.

1.9 Aim of the dissertation

This dissertation aims to introduce a previously developed wearable sensor system called the Motion Shirt to address the need for an objective, continuous, reliable, valid, and easy-to-apply motion assessment method for individuals with upper MSK extremities.

The series of studies seeks to establish and assess the validity, reliability, and applicability of the Motion Shirt using a pre-validated and standardized test known as the Functional Impairment Test-Hand and Neck/Shoulder/Arm (FIT-HaNSA) across three different chapters [53]. This test, previously validated, is recognized as a standard assessment for UE-MSK evaluations [53]. Additionally, a systematic review investigates other forms of easy-to-apply technologies in smartphones to explore new possibilities for remote and convenient tele-rehabilitation and assessment procedures for patients before and after SJR surgery.

An outline version of the dissertation objectives are as follows:

1. Validation of the Motion Shirt
2. Assessment of the Motion Shirt's Consistency Across Different Scenarios

3. Evaluation of the Motion Shirt's Post-Operative Monitoring Capabilities
4. Exploring Alternative Technologies of Wearable Sensors

The results of this dissertation underscore the effectiveness of the Motion Shirt in monitoring post-operative recovery, indicating its potential utility in accurately tracking recovery patterns in SJR or arthroplasty patients and guiding rehabilitation strategies for upper extremity MSK patients.

1.10 List of Tables

Table-1. Indications for Total Shoulder Replacement

Criteria	Description	Indication for TSR
Duration of Symptoms	Symptoms present for a prolonged period (e.g., >6 months) despite conservative treatment	Yes
Pain Level	Persistent pain affecting quality of life and daily activities	Yes
Functional Limitations	Significant limitations in range of motion and strength affecting daily activities	Yes
Imaging Findings	Severe joint damage or wear, including bone spurs, joint space narrowing, and soft tissue tears	Yes
Previous Treatments	Ineffectiveness of conservative treatments such as physical therapy, medications, or injections	Yes

1.11 List of Figures

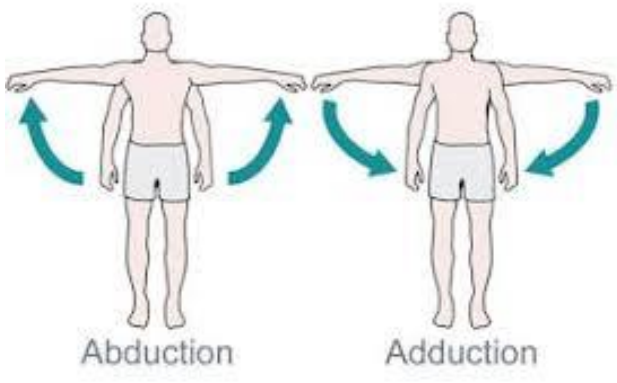

Figure 11-1. Shoulder Abduction/Adduction motion

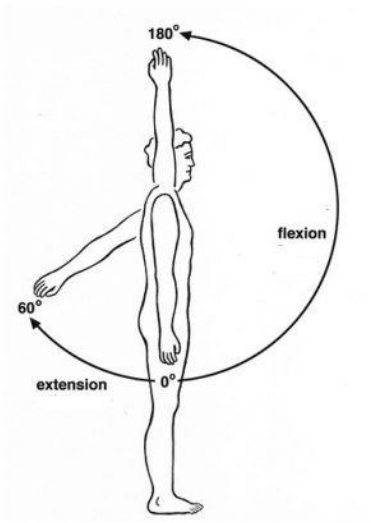

Figure 1-2. Shoulder Flexion/Extension motion

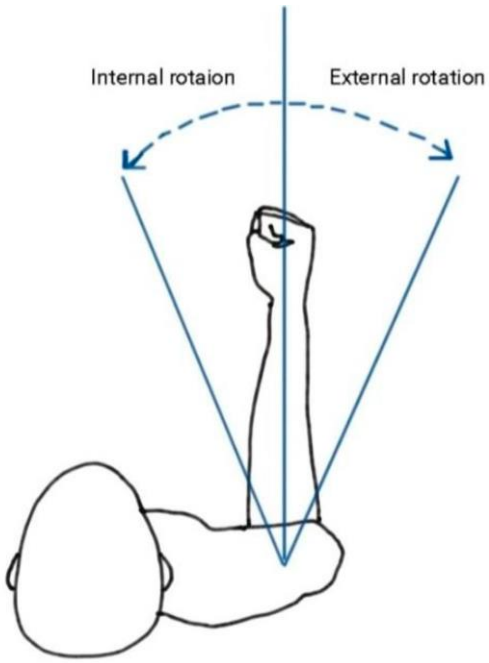

Figure 1-3. Shoulder Internal/External Rotation motion

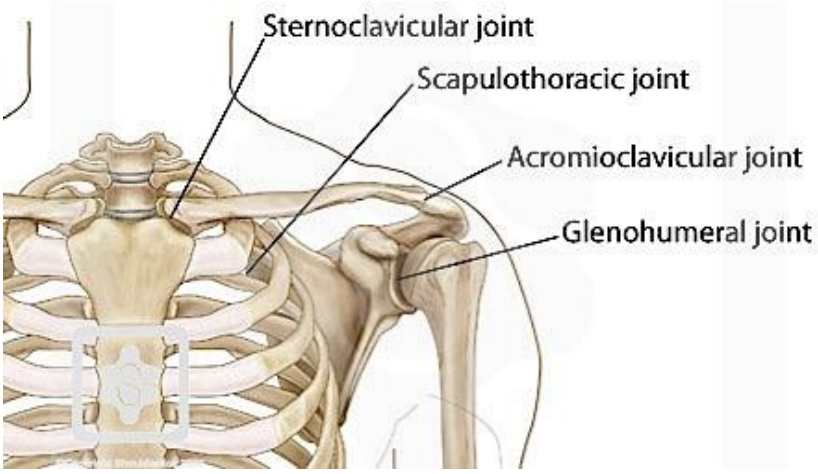

Figure 1-4. Shoulder complex and composing joints

Figure 1-5. IMU sensor used for the studies of the thesis (YOST LABS, CA, US)

Chapter 2

2 Assessing the Validity of a Wearable Shoulder Motion Tracking System Through Comparison with Dartfish in Patients Undergoing Shoulder Joint Replacement Surgery

This study has been submitted to Biomedical Physics & Engineering Express Journal.

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Abstract

Objective assessments of shoulder motion are paramount for effective rehabilitation and evaluation of surgical outcomes. Inertial Measurement Units (IMU) have demonstrated promise in providing unbiased movement data. This study is dedicated to evaluating the concurrent construct validity and accuracy of a wearable IMU-based sensor system, called "Motion Shirt", for the assessment

of shoulder motion arcs in patients awaiting shoulder replacement surgery. This evaluation was conducted by comparing Motion Shirt data with the Dartfish Motion Analyzer software during the Functional Impairment Test-Hand and Neck/Shoulder/Arm (FIT-HaNSA) test.

Thirteen patients (age>50), who were awaiting shoulder replacement surgery, were recruited. The Motion Shirt was employed to measure angular shoulder movements in two axes of Elevation and Plane of Elevation during the FIT-HaNSA test that is comprised of three different tasks resembling different daily life activities. Simultaneously, two cameras recorded the participants' movements to provide reference data. Bland-Altman plots were generated to visualize agreement between the Motion Shirt and the reference data obtained from the Dartfish Motion Analyzer software.

Bland-Altman plots revealed a substantial level of agreement between the Motion Shirt and Dartfish analysis in measuring shoulder motion. In Task-1, no significant systematic errors were exhibited, with only 3.27% and 2.18% of points exceeding the limits of agreement (LOA) in both elevation and the Plane of Elevation (POE), signifying a high level of concordance. In Task-2, a high level of agreement was also observed in Elevation, with only 3.8% of points exceeding the LOA. However, 5.98% of points exceeded LOA in POE for Task-2. In Task-3, focused on sustained overhead activity, the Motion Shirt showed strong agreement with Dartfish in Elevation (2.44% points exceeded LOA), but in POE, 7.32% points exceeded LOA.

The Motion Shirt demonstrated a robust concordance with Dartfish Motion Analyzer system in assessing shoulder motion during the FIT-HaNSA test. These results affirm the Motion Shirt's suitability for objective motion analysis in patients awaiting shoulder replacement surgery.

2.1 Introduction

Accurate and unbiased evaluation of shoulder joint mobility during dynamic movement is important to understand shoulder function and how it is disrupted by pathology. Wearable inertial measurement units (IMUs) have shown great promise in capturing and analyzing human movement, offering advantages such as objectivity, affordability, portability, and lightweight design. Recent studies on wearable sensor technology have demonstrated the ability of this technology to deliver unbiased, real-time movement analysis data for various medical and sporting purposes. IMU-based wearable sensors have been effectively used in several studies to evaluate joint kinematics, providing valuable insights into movement patterns and functional limitations [54–60].

Shoulder motion is complex and is critical to position the hand in space for many activities of daily life. To assess dynamic movement, a developed custom long sleeve compression instrumented with 5 IMU sensors by Langohr et al.[60], herein referred to as the 'Motion Shirt', was used to continuously measure shoulder angular movements in two horizontal and vertical planes. Given the complexity of shoulder movements, validity assessment of the Motion Shirt is a critical step. A first step in validating dynamic motion is the assessment of motion during a series of standardized tasks like the Functional Impairment Test-Hand and Neck/Shoulder/Arm (FIT-HaNSA) [53].

The aim of this project was to assess the concurrent construct validity and accuracy of the Motion Shirt system in detecting motion arcs during the FIT-HaNSA test in patients awaiting shoulder replacement surgery by comparing the arc of motion data collected from the Motion Shirt with the Dartfish Motion Analyzer software as a standard tool for motion measurements.

2.2 Methods

2.2.1 Study Design

In this prospective study, we explored the concurrent construct validity of the Motion Shirt by comparing humeral shoulder angles obtained from the Motion Shirt with those measured using a previously established, reliable, and valid system for range of motion (ROM) measurement, namely the Dartfish video analyzer. In accordance with ethical guidelines, the present study has

obtained approval from the Lawson and WREM Ethics Committee (# 121356) prior to the commencement of data collection.

2.2.2 Participants

From February 2023 to June 2023, patients were recruited from Hand and Upper Limb center in St.Joseph Hospital of London, Ontario. They were contacted based on specific criteria: inclusion criteria included being aged 50 or above, being on the waiting list for shoulder replacement surgery, and possessing fluency in English for test and intervention comprehension; exclusion criteria encompassed severe medical conditions like neurological disorders or motion and pain restrictions preventing participation in the Fit-HaNSA test and daily activities.

2.2.3 Study Procedures

Participants were informed about the study during their pre-operative clinic visit by the research office staff and provided written, informed consent upon expressing interest. The test protocol was designed to assess motion in two planes of "Elevation" and "Plane of Elevation," as defined by Langohr et al [60]. As defined, "Elevation" refers to the angular measurement formed by the intersection of the torso and the humeral shaft, while the "Plane of Elevation" specifies the direction of humeral elevation, with forward flexion (arm elevated to the front) defined as 0° (Figure 2-1). These two axes cover both angles required to describe a humero-thoracic motion in a three-dimensional space.

To achieve this, two cameras (GoPro 9, Go Pro Inc., San Mateo, California) were strategically placed on the side (on a tripod) and top (on the ceiling) of the test settings (JobSim system) to record participants' movements in both the Elevation and Plane of Elevation planes during the FIT-HaNSA test, capturing vertical and horizontal movements. The captured videos are imported into Dartfish Motion Analyzer software to obtain the arcs of motions and angles. This integrated approach allowed for the creation of a comprehensive and precise reference dataset against which the data collected from the IMU sensors of the wearable sensor system would be evaluated.

Participants were outfitted with the Motion Shirt in a clinical setting for comfort. Motion Shirt was prepared in different clothing sizes (Small, Medium, Large, Extra Large, etc.) to make sure each participant wears a comfortable version of the Motion Shirt. Participants were asked about their

comfortable size, and it was ascertained that the garment is comfortable and simultaneously tight enough to secure the sensors in the designated places. IMU sensors were securely placed in custom sewn pockets of the Motion Shirt (illustrated in detail in the following section), and the JobSim settings were configured for each task. Each participant received instructions for each task individually according to the research protocol. Participants assumed a "tin soldier" position, defined as 0° of abduction and 0° of internal-external rotation, and tasks were recorded by fixed cameras while the sensors were activated. After each task, sensors were deactivated during rest periods while settings for the next task were prepared. Upon completing all tasks, both sensor data and video footage were downloaded and analyzed, with the duration of each FIT-HaNSA task recorded.

2.2.4 Wearable Sensor System

The Motion Shirt, as a wearable sensors system developed by Langohr et al.[60], is a flexible, long-sleeved custom compression garment instrumented with five Inertial Measurement Units (IMUs) to precisely measure and monitor shoulder motions in the upper extremities (Figure-2) [60]. The IMUs are equipped with triaxial accelerometers, gyroscopes, and compasses capable of accurately tracking orientation in three-dimensional space with an accuracy of ±1° [60]. The IMUs were strategically placed: one near the sternum to track torso orientation, two on each arm at the mid-line humerus for humeral orientation, and two on the dorsal side of each wrist for forearm orientation. Additionally, adhesive markers were affixed to aid angle detection during motion analysis in Dartfish Motion Analyzer software. The Motion Shirt provides comfort and ease of use, allowing continuous, objective tracking of arm movements for extended periods. All IMUs can store orientation data on micro-SD cards, ensuring data integrity and facilitating subsequent analysis after synchronization prior to use.

2.2.5 Dartfish video analyzer

We used Dartfish, a precise movement analysis software, as a standard measurement tool, for precise kinematic assessment. Footage was obtained from cameras capturing Elevation and Plane of Elevation angles, enabling comparison with Motion Shirt data. Dartfish allows detailed frame-by-frame (5 frames per second) tracking and comprehensive shoulder movement coverage, validated for kinematic analysis in various studies and sports science applications [61].

To precisely track the angles, 3 indicators needed to be selected in the software. The selected points were the midpoints of the wrist, and around both shoulders glenohumeral joints at the top humerus position. This strategic choice both matched with the sensors positions on the motions shirt an also aimed to mitigate the influence of limb size variations among the participants. A representative set of chosen cues within the Dartfish Pro software, related to one of the study participants captured in both camera footages, is shown in Figure-3.

2.2.6 FIT-HaNSA Test

The FIT-HaNSA test is a reliable tool assessing shoulder-related functional capabilities, essential for tailoring effective rehabilitation strategies. It involves three tasks simulating lifting and sustained overhead activities using JobSim setting for task staging. Task 1 focuses on reaching and placing 1 kg jars on shelves at waist height. Task 2 replicates the reaching task at eye level and 25 cm below and Task 3 involves sustained overhead activity, screwing and unscrewing bolts in an attachment plate. The participant lifts jars at a standard speed of 60 beats per minute, with the task lasting a maximum of 300 seconds or until specific stopping criteria are met, ensuring safety and accurate evaluation of each participant's performance [62]. For Task-1 and Task-2, a set comprises six motions, specifically three picking and three dropping object motions. As for Task-3, a set involves three motions, namely fastening and unfastening two bolts in three holes.

2.2.7 Data analysis

The data initially collected from the sensors underwent thorough examination in a custom LabView application, allowing for visual inspection to identify any potential missed data, artifacts, or noise. In cases where the data were significantly affected by artifacts, trials were repeated at the test site in real-time to ensure a clean and reliable data collection process. Subsequently, the data obtained from the Motion Shirt sensors and Dartfish video analyzer were imported into MATLAB software (version R2022a, MathWorks Inc., Natick, MA). The sampling rate for both data measurement tools were set on 10Hz and the collected data were also synchronized through data stamps obtained through both measurement tools. The arcs of motion were defined by the angle difference of the start time, marked by the moment of picking up a jar, and the finish time, indicated by placing it on another shelf for tasks 1 and 2 of the FIT-HaNSA. The arc of motions recorded during the execution of the FIT-HaNSA test were then quantified and recorded for each participant.

To enhance data quality, we addressed the presence of noise by applying a smoothing algorithm to the noisy sections of dataset. This algorithm, based on signal filtering techniques, effectively mitigated the impact of noise on our dataset while also smoothing fluctuations.

After data cleaning steps, the arc of motion in both elevation and plane of elevation axes is determined by calculating the angular difference between the picking moment and dropping moment of the 3 objects used in Task-1 and 2 of FIT-HaNSA test. For Task-3, the angles of humerus during screwing and unscrewing bolts in both elevation and plane of elevation have been measured. The mean and standard deviation (SD) of the arc of motion for each participant were also calculated. The computation of the mean and standard deviation of the discrepancies between the two measurement systems for each participant was done to assess the overall concordance between the systems.

The determination of the minimum and maximum angles observed for each participant aids in assessing the extent of shoulder angle variation exhibited during the tasks, as well as evaluating the accuracy of the wearable sensor system in capturing the complete range of motion. The statistical analysis of individual participants' arcs of motion included calculating specific outcomes, such as the number of moves and sets. Additionally, key metrics, including the minimum, maximum, mean, and standard deviation of recorded arcs of motion, were compared between the Motion Shirt and Dartfish analyses to highlight the difference between these two measurement methods.

Bland-Altman plots were also created for each task of the FIT-HaNSA test, comparing shoulder angles obtained from the Motion Shirt and Dartfish video analyzer using data from each individual participant and all compiled motion data. These plots were generated to depict the relationship between the mean values of two measurement systems on the x-axis and the corresponding differences between them on the y-axis. The plot's bias line represents the average difference of the two measurements, while the lines at 1.96 multiplied by the standard deviation of the differences depict the limits of agreement (LOA=1.96*SD). These plots serve as a scatter plot representation, highlighting differences between the two measurement techniques in relation to their respective means. The Bland-Altman plot is a valuable tool for understanding potential

systematic discrepancies between the systems being studied and for identifying the limits of agreement within which most differences are observed.

To analyze the resulted Bland-Altman plots, the general distribution of points across the mean difference axis will be assessed along with the rate of points that exceed limits of agreement. The absence of a specific distribution pattern and a minimal rate of points exceeding LOAs (below 5%) substantiate the validity of motion shirt system as it shows that the measurements are sufficiently similar to the compared method of dartfish video analysis. Furthermore, the displacement of the mean difference line away from the zero value on the plot indicates the extent of the measurement bias between the two methods.

2.3 Results

Based on sample size calculations we determined a sample of 20 participants to be recruited for this study. However, thirteen participants consented to perform the test while wearing Motion Shirt and their video footages were recorded for further analyses. The mean age was 66±8 years and 8/13 (61%) of the participants were male. Osteoarthritis was the primary diagnosis for 8 patients and the other had shoulder pain due to rotator cuff tears.

We delineate the findings into two categories: (a) Participant-specific performance and (b) aggregated results for the entire sample of recorded arcs of motion. This presentation allows for comprehensive comparisons of the collected data through both methods, employing both individual and holistic approaches.

2.3.1 Participant-specific performance

The motion data obtained from each participant through both methods of video analysis and the Motion Shirt have been presented in Tables 2, 3, and 4. The tables provide an overview of all participants' performances in two planes, namely Elevation and Plane of Elevation, related to Task-1, Task-2, and Task-3, respectively. The statistics summary and number of recorded arcs of motions related to each participant through both methods of Dartfish video analysis and motion shirt are presented in the tables to evaluate the difference of measurements for each participant via statistical metrics. Additionally, the tables in this section illustrate the frequency of motions observed for each participant, along with the number of completed sets.

Participants in Task 1 demonstrated an average elevation arc of motion of 30.9° ± 3.05° as analyzed by Dartfish, while the Motion Shirt recorded a slightly lower average of 29.6° ± 3.11°. In the Plane of Elevation, the Dartfish analysis showed an average arc of 23° ± 5.67°, which closely matched the Motion Shirt's recorded average of 23° ± 5.56°. The minimum and maximum arcs recorded were similar between the two methods for both elevation and plane of elevation (Table-2-2).

In Task 2, data from participants #1, #7, and #11 were excluded due to their inability to complete the task at the required arm reach level. For the remaining 10 participants, Dartfish analysis showed an average elevation arc of motion ranging from 36.2° ± 5.51° to 53.1° ± 5.58°, with a mean of 45.4° ± 5.37°. The Motion Shirt recorded slightly lower values, with an average arc of motion ranging from 32.8° ± 4.46° to 51.4° ± 5.62° and a mean of 42.5° ± 4.38°. For the Plane of Elevation, Dartfish yielded an average arc ranging from 13.9° ± 4.55° to 32.4° ± 7.16°, while the Motion Shirt recorded similar values, with an average range of 14.7° ± 4.73° to 32.4° ± 6.77° and a mean of 21.6° ± 4.94° (Table 2-3).

In Task 3, constant Elevation and Plane of Elevation angles were analyzed since no arc of motion occurs during the screwing and unscrewing of bolts. Dartfish analysis showed that the average elevation plane angles ranged from 50.7° ± 13.38° to 68.1° ± 11.92°, with a mean angle of 57° ± 11.11°. The Motion Shirt sensors recorded similar results, with averages ranging from 50.7° ± 12.33° to 67.5° ± 10.57° and a mean of 58.9° ± 10.99°. For the Plane of Elevation, Dartfish reported angles ranging from 7.3° ± 6.68° to 19.8° ± 10.15°, with a mean of 13.4° ± 8.12°, while the Motion Shirt recorded angles from 8.5° ± 5.6° to 21.1° ± 11.10°, with a mean of 14.9° ± 8.79° (Table 3-3).

2.3.2 Bland-Altman plots: Aggregated motions

Among the 13 individuals who took part in Task 1, it was observed that 10 participants exhibited a performance level below 30 motions. Likewise, in both Task 2 and Task 3, it was observed that 12 out of 13 participants executed a quantity of motions that was below 30. Consequently, the Bland-Altman plots generated for these participants may not offer a comprehensive overview for comparing the two measurements, given the restricted quantity of data points available. In order to overcome this constraint and achieve a more holistic comprehension, we aggregated all the

motion measurements pertaining to each task, encompassing both the vertical and horizontal planes of elevation. By conducting this procedure, a total of six distinct Bland-Altman plots were generated, considering the combination of three tasks and two planes.

Tables 5 through 7, demonstrate the summary outcome statistics of both methods obtained from the compiled data such as minimum, maximum, mean, standard deviation, and standard error of measurement (SEM), as well as the Bias line and LOAs calculated for plotting the Bland-Altman plot. Furthermore, the table also presents the count and the rate (percentage) of points that exceeded LOA boundaries. Figures 5 through 7 depict the Bland-Altman plots for each task in both the elevation and plane of elevation.

The Bias line(±LOA) for Figure 5 (Elevation and POE) are 2.07° (±5.59°) and -0.62° (±6.21°), respectively. In total, 15 points (%3.27) in Elevation and 10 points (%2.18) in POE have exceeded the LOAs in their corresponding Bland-Altman plot. Figure 5 shows that the aggregated points do not follow a specific pattern and have been distributed nearly equally along 0° axis as the bias lines (2.07° and -0.62°) are close to 0°. The rate of exceeded LOA points in both planes is lower than 5%. Furthermore, the summary statistics values for both methods differ by no more than a rate of 3° in Task-1.

The Bland-Altman plots for the aggregated arc of motions in the Elevation and Plane of Elevation planes for Task-2 are depicted in Figure-6, respectively. The bias lines (±LOA) for Elevation and POE are 1.98° (±6.92°) and -0.72° (±5.30°). No discernible patterns are observed in either of the figures and the bias lines are similarl to Task-1 close to 0° (1.98° and -0.72°). In Figure-6 (Elevation), 7 points (3.80%) have surpassed the Limits of Agreement (LOAs), while in Figure-6 (POE), 11 points (5.98%) have exceeded the LOAs as indicated in their respective Bland-Altman plot which surpasses the limit of 5% of total points.

The findings for Task-2 have been summarized in Table-6. Similar to Task-1, the key statistical metrics represent a difference lower than a rate of 3°.

Figure-7 display the Bland-Altman plots for the aggregated arc of motions in the Elevation and Plane of Elevation planes, respectively, for Task-3. The Bias lines with their corresponding Limits of Agreement (LOA) are presented as 0.3° (±7.28°) for Figure-7 (Elevation) and -1.6° (±6.28°) for

Figure-7 (POE). Both plots show no discernible patterns, and the bias lines are close to 0° showing minimal bias difference level. The combined data comprises 3 points (2.44%) in Elevation and 9 points (7.32%) in POE exceeding the LOAs in their respective Bland-Altman plots. Therefore, more than 5% of points in the Bland-Altman plot related to Plane of Elevation of Task-3 have exceeded the LOA lines. The results pertaining to Task-3, regarding the Elevation and the Plane of Elevation, have been outlined in Table-7.

2.4 Discussion

The objective of this study was to assess the validity of the "Motion Shirt," a wearable sensor system, by comparing the recorded performance of a group of patients awaiting shoulder replacement surgery using this system with a standard measurement method (dart fish) via the FIT-HaNSA pre-validated standard test. This comparison was based on the evaluation of the arc of motion in both the Elevation and Plane of Elevation planes across three distinct tasks. The study's results suggest that the Motion Shirt is a valid wearable sensor system for assessing and recording the arc of motion in both the Elevation and Plane of Elevation planes across various shoulder-related tasks. This technology holds promise in providing objective motion data.

Our analysis revealed intriguing patterns in the range of motion across Elevation and Plane of Elevation (POE) in these tasks, shedding light on how the nature of the task significantly influences motion patterns.

Task-1 required participants to pick up objects from waist level and drop them at a higher position, resulting in predominant Elevation motions falling mostly within the 25° to 35° range. Similarly, in Task-2, where actions were performed at eye level and 25 cm below, Elevation motions shifted logically to the 35° to 55° range. This may indicate why a lower number of motions is recorded in total in comparison to Task-1 motions (184 vs 458) as it necessitates a higher arm reach to pick up and drop the objects in the FIT-HaNSA test, and it is more difficult for the participants as it is performed in a higher height. However, POE motions remained relatively consistent across both tasks, emphasizing the influence of task requirements on motion patterns.

In Task-3, involving continuous screwing and unscrewing actions, the reported angles focused on a narrower range, indicating participants maintained a relatively fixed posture throughout the task. This stability in angles further highlights the unique nature of this task compared to the others.

In the comparative analysis of measurement methods, the participant-specific approach revealed a close approximation of measurements for both methods. However, individual variations, influenced by participants' shoulder status (mild or severe pain), led to divergent performances, impacting the number of completed motions and sets, as well as the angle variation in all three tasks. Despite these differences, the close alignment of minimum, maximum, mean, and standard deviation values for performed motions in both methods reinforces the validity of motion shirt measurements.

The aggregated motion approach, coupled with the examination of Bland-Altman plots, underscored a high level of concordance between Dartfish analysis and the Motion Shirt sensor set. As observed in all plots, there is a nearly uniform and unbiased distribution of points, accompanied by a low mean difference (bias) value and the majority of points falling within the limits of agreement. Task-1 results, particularly in both Elevation and Plane of Elevation (POE), exhibited substantial agreement, characterized by a nearly uniform pattern of distribution and a rate of points exceeding the limits of agreement (LOAs) below 5%. Similar agreements were observed for Task-2 and Task-3 in the Elevation plane, showcasing uniform distribution and a rate of points exceeding LOAs below 5%. However, in the POE results of Task-2 and Task-3, a higher than 5% rate of points exceeding LOAs was noted. The approach of aggregated data to obtain the Bland-Altman plots has contributed to a more thorough comprehension of the concordance between the Motion Shirt data and Dartfish analysis, thereby augmenting the credibility of our results.

In summary, these outcomes highlight the Motion Shirt's capability to accurately capture motion data across various tasks and its validity when compared with Dartfish video analysis.

The variations observed in performed motions and measured angles can be attributed to several factors, including the participant's distance from the JOBSIM system. A compensatory strategy was noted, where participants shortened their distance from the system, affecting reach and subsequently altering arcs of motion. Additionally, unrestricted elbow movement resulted in

diverse postures and movement patterns during tasks. Different sizes of arm reach also play a role in the motion patterns. All mentioned factors along with the severity of pain, and shoulder pathological status contribute to the observed variance in the arcs of motions.

All in all, the comparison of the two measurements via both approaches revealed consistent concordance, reinforcing the robustness of the Motion Shirt data. These findings align with comparable studies, supporting the accuracy and reliability of wearable sensor systems in motion analysis.

In recent years, a series of studies have delved into the applications of Inertial Measurement Units (IMUs) in healthcare contexts, particularly in the assessment of joint movements and kinematics. These studies collectively offer valuable insights into the potential benefits and limitations of IMUs in various clinical settings.

The study conducted by Chan et al. focused on the comparison between a commercial IMU system and an optical motion capture (OMC) device for evaluating shoulder angular motions (four active movements including: 90° flexion, extension, external rotation, and 90° abduction) in young healthy participants and in clinical practice. Their findings revealed significant differences between IMU and OMC measurements, exceeding the acceptable limits for 95% of the population according to Bland-Altman analysis. However, it was noteworthy that the mean bias demonstrated substantial agreement for over 60% of participants across different movements. Intriguingly, while abduction and flexion exhibited statistically significant differences, extension and external rotation showed significant levels of agreement. This study hints at the potential utility of IMUs in remote rehabilitation applications [63].

Morrow et al. conducted a study that explored the accuracy of a commercially available IMU system (worn on the base of the back of the participant's head, anterior sternum, and the lateral aspect of the bilateral upper-arms and forearms) in comparison to a traditional lab-based motion capture system. This investigation centered on assessing angular kinematics of six surgical faculty members during a surgical training task. The task simulated the peg transfer activity, wherein participants were required to grasp and transfer six small triangle-shaped objects on a pegboard. The sequence involved initiating the transfer with the non-dominant hand and passing the objects midair to the dominant hand, followed by the reverse process. The study revealed precise

measurements provided by the IMU system for shoulder elevation and elbow flexion. However, as the measurements obtained by the OMC system increased, an inversely proportional inaccuracy was observed. Interestingly, Bland-Altman analysis did not uncover any substantial systematic errors. This research underscored the importance of employing specific methodologies when evaluating IMU-based motion assessor systems [64]

Turning attention to the correlation between IMU-based systems and subjective outcome measurements, Jolles et al. conducted a study that explored this relationship. A group of osteoarthritis patients' motions were compared with a control group; both performed 7 out of 12 of the standardized activities described in the SST. The data was collected by two 3-dimensional gyroscopes and accelerometer sensors placed on lateral aspects of the distal humerus. They compared relative shoulder kinematic scores like a range of angular velocity score, a power score, and a moment score that express the performance of the operated side as a percentage of the performance of the healthy side. The study yielded high to excellent correlations (ranging from 0.61 to 0.80) between clinical and kinematic scores derived from the sensors. This investigation suggested that sensor-based systems offer an effective means of measuring the functional performance of patients with shoulder conditions and may serve as valuable tools for monitoring treatment and rehabilitation processes [35].

Seel et al. conducted a study to calculate knee joint angles for human motion analysis using inertial measurement data. The obtained data from IMU sensors (placed on femur and fibula) were compared with an optical motion capture measurement system (markers placed on anatomical landmarks). Their findings showcased precise measurements with minimal errors. Root mean square errors for knee flexion/extension angles were less than 1° on the prosthesis and approximately 3° on the human limb. Additionally, deviations of about 1° were observed for ankle plantar/dorsiflexion. This study highlighted the potential of IMUs in accurately assessing joint angles for motion analysis applications [38].

The results of abovementioned studies align with the findings of the present study, as they also report relatively low error rates across various considerations and comparisons indicating the validity of using IMU sensors for motion measurements. These studies collectively underscore the promise of IMUs in healthcare settings, offering insights into their accuracy and potential utility

for assessing joint movements, kinematics, and their correlations with patient-reported outcomes. However, it is imperative to consider the choice of IMU system and employ specific methodologies to ensure reliable and meaningful results in various clinical scenarios.

Limitations of our study include the limited number of participants completing more than 30 motions in Task-2 and Task-3, impacting data aggregation and statistical analysis (). Future studies with larger sample sizes can further explore participant performance coherence. Moreover, indicating a certain unique place for standing in front of the JOBSIM device might avoid the variations of motions to minimize participants' compensation strategies.

In conclusion, our study demonstrates strong agreement between the Motion Shirt and the Dartfish analysis, supporting the validity of this wearable sensor system for motion analysis in various shoulder-related tasks. The task-specific patterns of motion observed highlight the influence of task nature on movement patterns, providing valuable insights for future studies in this domain. The Motion Shirt offers a promising solution to enhance patient care, aid rehabilitation, prevent injuries, educate patients on correct movement patterns, and contribute to research in the field of musculoskeletal health. Its potential to revolutionize remote monitoring and provide real-time feedback makes it a valuable tool in the hands of healthcare professionals.

The Motion Shirt, as a wearable sensor system, holds significant potential for various clinical implications, offering a valuable tool for comprehensive motion analysis and monitoring patients' movements in real-life scenarios.

2.5 Conclusion

This study aimed to evaluate the accuracy of the Motion Shirt in capturing shoulder motion by conducting a comparative analysis with a widely used measurement technique. The findings indicate a high level of concurrence between the Motion Shirt and the Dartfish analysis, confirming the credibility and consistency of the system in evaluating motion in various tasks associated with shoulder functionality.

In addition, our recordings and analysis have revealed distinct motion patterns for each task of the FIT-HaNSA test, highlighting the substantial impact of task characteristics on individuals' movement performance. The developed wearable platform offers a significant basis for future

scholarly investigations within the discipline, facilitating the advancement of customized rehabilitation protocols and ways for preventing injuries by enabling an alarming biofeedback system using wearable sensor systems.

The Motion Shirt has a wide range of possible uses within the healthcare field. The utilization of this technology has the potential to enhance patient care through various means, including remote monitoring, real-time feedback, and post-surgery rehabilitation. Furthermore, it functions as an instructional instrument, fostering patient compliance with prescribed exercises and facilitating the adoption of improved movement techniques.

The present study provides useful insights; nonetheless, it is imperative to note certain limitations inherent within the research. Future research endeavors should aim to include larger and more diverse participant groups to enhance the validity of the Motion Shirt's application across a range of therapeutic contexts.

In summary, the Motion Shirt presents itself as a potentially effective alternative for doing thorough motion analysis within the field of musculoskeletal health. The asset of this technology lies in its potential to revolutionize patient care and contribute to evidence-based practice, rendering it highly beneficial for healthcare practitioners and researchers.

Data Availability Statement: The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Disclosure Statement: The authors declare that they have no financial or personal relationships that could potentially bias or influence the content of this research article. This study was conducted independently, and no conflicts of interest exist regarding the publication of this manuscript. Additionally, no funding or financial support was received for this research project.

2.6 List of Tables

Table 2-1. Baseline Characteristics of study's participants (n=13)

Age (mean±SD), y	66.54±8.06
Sex, n	
Males	8 (62%)
Females	5 (38%)
Side tested for the FIT-HaNSA, n	
Right	8
Left	5

Table 2-2. The overall results of each participant's performance in Task-1 (V: Video analysis results using Dartfish Software, S: Shirt recorded results); except the N moves, and N sets columns all other units are in degrees (°). [LOA= Limits of Agreement, Min=Minimum, Max=Maximum, POE= Plane of Elevation, SD=Standard Deviation]

			ELEVATION								**POE**							
	N moves	N sets	Min	Max	Mean	SD	LOA	D (Bias)	Upper Bound	Lower Bound	Min	Max	Mean	SD	LOA	D (Bias)	Upper Bound	Lower Bound
PATIENT 1 - V	25	4	22.8	37.2	28.29	3.81	**5.47**	**3.33**	8.81	-2.14	16.9	37.6	24.07	5.21	**3.52**	**0.66**	4.18	-2.86
PATIENT 1 - S	25	4	17.7	33.8	24.95	4.3					15.2	36.7	23.41	5.45				
PATIENT 2 - V	21	3	26.4	43.4	34.2	5.15	**5.039**	**-0.42**	4.62	-5.46	29.1	46.1	35.56	5.1	**4.67**	**0.92**	5.59	-3.75
PATIENT 2 - S	21	3	23.6	41.9	34.77	4.59					29.1	45.5	34.64	4.09				
PATIENT 3 - V	12	2	22	35.4	27.49	4.43	**4.11**	**-0.21**	3.9	-4.32	13.9	30.9	20.16	5.95	**4.3**	**-0.08**	4.22	-4.37
PATIENT 3 - S	12	2	23.5	32.8	27.93	3					13.8	33.1	20.23	6.92				
PATIENT 4 - V	126	21	27.4	41.9	32.89	3.51	**4.77**	**2.78**	7.55	-1.99	10.2	42.9	19.08	6.62	**4.12**	**-2.52**	1.6	-6.64

PATIENT 4 - S	126	21	24.8	39	30.83	3.23					12.2	42.9	21.57	6.36				
PATIENT 5 - V	29	4	20.14	53.13	36.36	8.27	**7.8**	**3.88**	11.68	-3.93	16	38	26.52	5.68	**6.58**	**-1.87**	4.71	-8.45
PATIENT 5 - S	29	4	20.4	55.4	32.48	8.21					17.3	40.5	28.39	6.63				
PATIENT 6 - V	30	5	23.7	33.2	28.39	2.28	**4.49**	**-0.18**	4.3	-4.68	14.8	37	22.1	5.82	**5.1**	**-1.57**	3.54	-6.68
PATIENT 6 - S	30	5	23.2	35.5	28.6	3.14					15.2	35.8	23.67	5.66				
PATIENT 7 - V	3	0	29.4	33.7	31.55	3.04	**7.67**	**-0.5**	7.17	-8.17	13	25.6	17.7	6.88	**5.6**	**1.7**	7.3	-3.9
PATIENT 7 - S	3	0	30.2	36.1	32.93	2.97					11.2	22.2	16	5.63				
PATIENT 8 - V	36	6	22.9	34.1	28.7	2.99	**5.58**	**1.65**	7.22	-3.93	10.4	36.3	19.01	7.17	**5.26**	**-1.62**	3.64	-6.88
PATIENT 8 - S	36	6	19.2	34.6	27.29	3.52					11.1	39.9	20.63	7.67				

PATIENT 9 - V	30	5	22.1	36.6	29.52	3.05	**3.7**	**0.03**	3.73	-3.66	18.8	42.1	30.95	7.01	**5.79**	**-0.6**	5.19	-6.39
PATIENT 9 - S	30	5	24	35.3	29.64	3.39					20	43	31.55	6.82				
PATIENT 10 - V	48	8	25.3	35.2	29.81	2.59	**5.8**	**2.32**	8.12	-3.49	15.1	38.5	23.72	6.05	**5.3**	**1.43**	6.72	-3.87
PATIENT 10 - S	48	8	21.5	33.3	27.66	3.29					14.4	40	22.33	5.94				
PATIENT 11 - V	12	2	22.5	34.9	28.47	3.8	**4.24**	**3.02**	7.26	-1.23	21.9	32.6	25.9	2.74	**8**	**4.43**	12.44	-3.57
PATIENT 11 - S	12	2	20.1	33.3	26.13	3.76					14.8	28.8	21.47	3.75				
PATIENT 12 - V	72	12	25.8	33.7	30.55	1.93	**4.1**	**2.61**	6.71	-1.49	9.5	34	17.56	5.27	**6.71**	**0.82**	7.53	-5.89
PATIENT 12 - S	72	12	22.1	31.6	27.77	2.37					8.1	30.5	17.56	6.16				
PATIENT 13 - V	15	2	29.8	47.3	36.18	5.38	**5.44**	**1.7**	7.14	-3.74	9.5	28.3	16.29	6.51	**4.75**	**-0.73**	4.02	-5.48
PATIENT 13 - S	15	2	27.1	41.4	33.88	4.54					11.8	30	17.02	5.45				

Table 2-3. The overall results of each participant's performance in Task-2 (V: Video analysis results using Dartfish Software, S: Shirt recorded results); except the N moves, and N sets columns all other units are in degrees (°). [LOA= Limits of Agreement, Min=Minimum, Max=Maximum, POE= Plane of Elevation, SD=Standard Deviation]

TASK 2																		
			Elevation								POE							
	N moves	N sets	Min	Max	Mean	SD	SD*1.96	D	Upper Bound	Lower Bound	Min	Max	Mean	SD	SD*1.96	D	Upper Bound	Lower Bound
PATIENT 1 - V																		
PATIENT 1 - S																		
PATIENT 2 - V	12	2	43.16	57.44	50.45	3.28	**3.01**	4.92	7.93	1.91	14	37.2	22.94	8.62	**5.49**	**0.12**	5.61	-5.37
PATIENT 2 - S	12	2	38.9	54.2	45.53	3.75					13.7	39.3	22.83	8.22				
PATIENT 3 - V	6	1	40.8	53.4	45.93	4.35	**1.9**	5.43	7.33	3.53	23.5	33.2	27.48	3.26	**3.55**	**0.5**	4.06	-3.06
PATIENT 3 - S	6	1	34.1	48	40.5	4.61					23.4	32.5	26.98	3.5				
PATIENT 4 - V	27	4	30.6	51.5	44	4.81	**4.52**	1.51	6.04	-3.01	16.4	39.6	25.22	5.87	**4.47**	**-1.29**	3.19	-5.76
PATIENT 4 - S	27	4	30.2	50.2	42.49	4.54					20	37.8	26.51	4.99				

PATIENT 5 - V	8	1	36	61.84	52.97	9.03	**5.61**	6.47	12.08	0.86	15.4	26.7	21.41	3.83	**4.12**	**1.56**	5.68	-2.55
PATIENT 5 - S	8	1	33.6	57.2	46.5	8.18					16.3	26.2	19.85	3.64				
PATIENT 6 - V	18	3	29.7	46.2	39.89	4.44	**5.76**	0.43	6.19	-5.32	11.3	30	18.26	6.3	**5.41**	**-1.64**	3.77	-7.05
PATIENT 6 - S	18	3	27.7	47.8	39.46	5.39					10.5	33.8	19.9	6.2				
PATIENT 7 - V																		
PATIENT 7 - S																		
PATIENT 8 - V	18	3	39.2	52.9	44	4.12	**6.06**	4.93	10.99	-1.13	11.2	39.5	20.86	8.5	**5.16**	**-0.03**	5.13	-5.19
PATIENT 8 - S	18	3	32.1	47.4	39.07	4.85					11.7	36.8	20.89	8.03				
PATIENT 9 - V	18	3	38.2	56.3	47.61	5.64	**8.95**	2.23	11.18	-6.71	17.8	42.3	27.47	7.41	**6.47**	**-1.07**	5.4	-7.55
PATIENT 9 - S	18	3	34.6	58.6	45.37	6.34					17.6	41	28.54	7.58				
PATIENT 10 - V	24	4	43.2	58.4	52.23	4.27	**6.16**	1.61	7.77	-4.55	11.1	30.3	19.47	5.26	**4.91**	**-1.94**	2.97	-6.86
PATIENT 10 - S	24	4	40.1	58.2	50.62	5.42					15.5	30.7	21.41	4.52				

PATIENT 11 - V																		
PATIENT 11 - S																		
PATIENT 12 - V	45	7	29	47.9	38.93	5.56	**5.34**	-0.26	5.08	-5.6	8	22.1	11.79	3.18	**4.05**	**-0.5**	3.55	-4.56
PATIENT 12 - S	45	7	26.1	50.6	39.33	6.36					8.5	20.2	12.3	3.12				
PATIENT 13 - V	8	2	32.2	44.8	38.41	4.77	**5.87**	2.09	7.96	-3.78	10.2	23	16.65	4.92	**2.51**	**-0.09**	2.42	-2.6
PATIENT 13 - S	8	2	30.7	41.3	36.33	3.45					10.2	25.3	16.74	5.38				

Table 2-4. The overall results of each participant's performance in Task-3 (V: Video analysis results using Dartfish Software, S: Shirt recorded results); except the N moves, and N sets columns all other units are in degrees (°). [LOA= Limits of Agreement, Min=Minimum, Max=Maximum, POE= Plane of Elevation, SD=Standard Deviation]

TASK 3																		
			Elevation								POE							
	N moves	N sets	Min	Max	Mean	SD	SD*1.96	D	Upper Bound	Lower Bound	Min	Max	Mean	SD	SD*1.96	D	Upper Bound	Lower Bound
PATIENT 1 - V	5	1	41.2	53	48.24	4.95	**3.71**	**-3.88**	-0.17	-7.59	-1.4	16	5.2	7.09	**4.66**	**0.72**	5.38	-3.94
PATIENT 1 - S	5	1	45	58	52.12	5.51					0.4	13.2	4.48	5.15				
PATIENT 2 - V	2	0	48.5	58.2	53.6	6.86	**N/A**	**N/A**	N/A	N/A	8.4	12.6	10.5	2.97	**N/A**	**N/A**	N/A	N/A
PATIENT 2 - S	2	0	45.8	54.5	50.15	6.15					12.1	16.3	94.2	2.97				
PATIENT 3 - V	10	3	42.2	65.7	54.59	7.73	**6.05**	**1.48**	7.53	-4.57	11.7	24.1	16.66	3.98	**4.27**	**2.35**	6.62	-1.92
PATIENT 3 - S	10	3	43.5	66.6	53.11	7.92					10.2	19	14.31	2.94				
PATIENT 4 - V	36	12	38.1	59.9	47.89	6.24	**4.9**	**-1.03**	3.87	-5.94	6.2	19.5	12.83	4.41	**3.81**	**-1.78**	2.03	-5.59
PATIENT 4 - S	36	12	37.9	60.8	48.92	6.01					8	23.1	14.61	4.25				

PATIENT 5 - V	2	0	48	62	55	9.9	**N/A**	**N/A**	N/A	N/A	7	13.2	10.1	4.24	**N/A**	**N/A**	N/A	N/A
PATIENT 5 - S	2	0	52.7	61.7	57.2	6.36					2.1	5.3	3.6	2.12				
PATIENT 6 - V	15	5	53.8	73.1	62.94	6.69	**2.68**	**-0.23**	2.45	-2.92	6	17.3	10.65	3.57	**2.22**	**0.16**	2.38	-2.06
PATIENT 6 - S	15	5	56.2	71.5	63.49	5.49					5.8	17.7	10.26	3.1				
PATIENT 7 - V	2	0	60	68.1	64.05	5.73	**N/A**	**N/A**	N/A	N/A	-0.9	4	1.55	3.46	**N/A**	**N/A**	N/A	N/A
PATIENT 7 - S	2	0	64.2	73.4	68.8	6.5					4.6	9.4	7	3.39				
PATIENT 8 - V	3	1	82.8	98.3	90.47	7.75	**0.68**	**5.5**	6.18	4.82	23.1	32	27.5	4.45	**0.14**	**-5.45**	-5.31	-5.59
PATIENT 8 - S	3	1	77.5	92.4	84.97	7.45					20.2	37.5	29.57	8.74				
PATIENT 9 - V	12	4	41.3	64.1	52.08	8.07	**8.63**	**-1.68**	6.95	-10.32	12.5	37.2	25.5	7.99	**5.12**	**-2.9**	2.22	-8.02
PATIENT 9 - S	12	4	43.5	65	53.76	7.14					14.4	39.1	28.4	7.16				
PATIENT 10 - V	9	3	44.1	64.5	54.3	7.85	**5.32**	**4.93**	10.25	-0.39	6.7	36	23.12	9.7	**8.4**	**-3.67**	4.73	-12.07
PATIENT 10 - S	9	3	36.7	61.7	49.37	9.84					8.5	38.8	26.79	9.8				

PATIENT 11 - V	6	2	41.1	66.3	52.4	9.52	**3.27**	**-2.87**	0.4	-6.13	-2.9	8.8	3.73	4.25	**2.43**	**-3.7**	-1.27	-6.13
PATIENT 11 - S	6	2	42.1	68.3	56.26	9.76					2.5	12.2	7.43	3.59				
PATIENT 12 - V	18	6	47.5	66.2	52.4	6.96	**6.28**	**3.3**	9.58	-2.98	11.2	21.2	15.62	2.92	**3.61**	**-2.72**	0.89	-6.33
PATIENT 12 - S	18	6	46.1	60.6	53.13	4.48					13.3	22.4	18.33	2.52				
PATIENT 13 - V	3	1	69.9	85.3	52.4	7.7	**3.31**	**3.37**	6.68	0.06	6.6	15.9	10.8	4.71	**5.22**	**-4.4**	0.82	-9.62
PATIENT 13 - S	3	1	67.3	83.1	74.23	8.08					8.2	20.6	15.2	6.35				

Table 2-5. Statistical and Bland-Altman results of Dartfish, and Motion Shirt measurement methods related to Task-1 of FIT-HaNSA test. [LOA= Limits of Agreement, SD=Standard Deviation, SEM=Standard Error of Measurement]

Plane	Measurement Type	Minimum (°)	Maximum (°)	Mean (SD)	SEM (°)	Bias line (±LOA)	Exceeded LOA points (%)
Elevation	Dartfish	20.14	53.13	31(4.34)	0.21	2.07° (±5.59°)	15(%3.27)
	Motion Shirt	17.7	55.4	28.9(4.39)	0.20		
Plane of Elevation	Dartfish	9.5	46.7	22.1(7.7)	0.36	-0.62° (±6.21°)	10(%2.18)
	Motion Shirt	8.1	45.5	22.7(7.63)	0.36		-

Table 2-6. Statistical and Bland-Altman results of Dartfish, and Motion Shirt measurement methods related to Task-2 of FIT-HaNSA test. [LOA= Limits of Agreement, SD=Standard Deviation, SEM=Standard Error of Measurement]

Plane	Measurement Type	Minimum (°)	Maximum (°)	Mean (SD)	SEM (°)	Bias line (±LOA)	Exceeded LOA points (%)
Elevation	Dartfish	29.00	61.84	44.4(7.09)	0.52	1.98° (±6.92°)	7 (3.8%)
	Motion Shirt	26.10	58.60	42.4(6.84)	0.50		
Plane of Elevation	Dartfish	8.00	42.30	19.7(7.83)	0.58	-0.72° (±5.30°)	11 (5.98%)
	Motion Shirt	8.50	39.60	20.4(7.67)	0.57		

Table 2-7. Statistical and Bland-Altman results of Dartfish, and Motion Shirt measurement methods related to Task-3 of FIT-HaNSA test. [LOA= Limits of Agreement, SD=Standard Deviation, SEM=Standard Error of Measurement]

Plane	**Measurement Type**	**Minimum (°)**	**Maximum (°)**	**Mean (SD)**	**SEM (°)**	**Bias line (±LOA)**	**Exceeded LOA points (%)**
Elevation	Dartfish	38.1	98.3	54.9(10.77)	0.97	0.3° (±7.28°)	3(%2.44)
	Motion Shirt	36.7	92.4	54.6(9.9)	0.89	-	
Plane of Elevation	Dartfish	-3.1	41.1	14.6(7.95)	0.72	-1.6° (±6.28°)	9(%7.32)
	Motion Shirt	0.4	39.8	16.2(8.34)	0.75		-

2.7 List of Figures

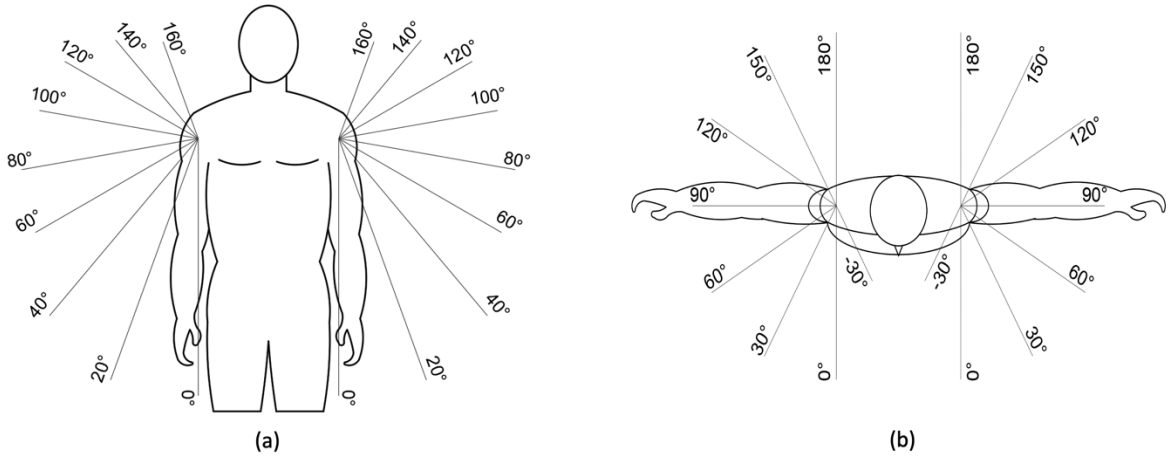


Figure 2-1. The Specified orientation and range of "Elevation" (a) and "Plane of Elevation" (b) as per Langohr et al.

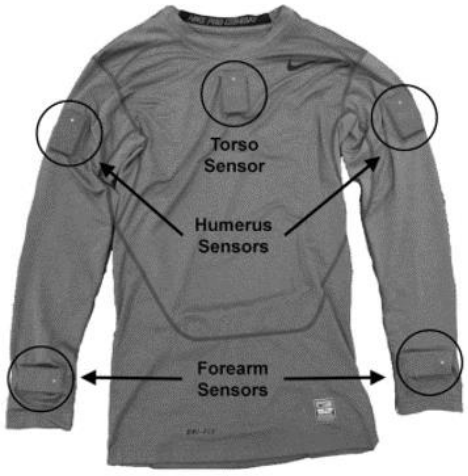


Figure 2-2. The developed wearable sensor system, "Motion Shirt", including 5 IMU sensors placed into sewn pockets on the designated locations.

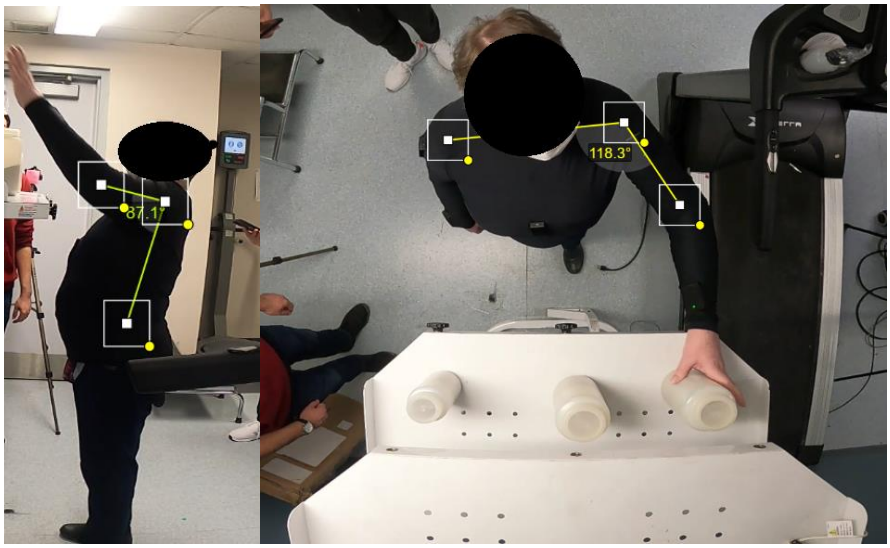
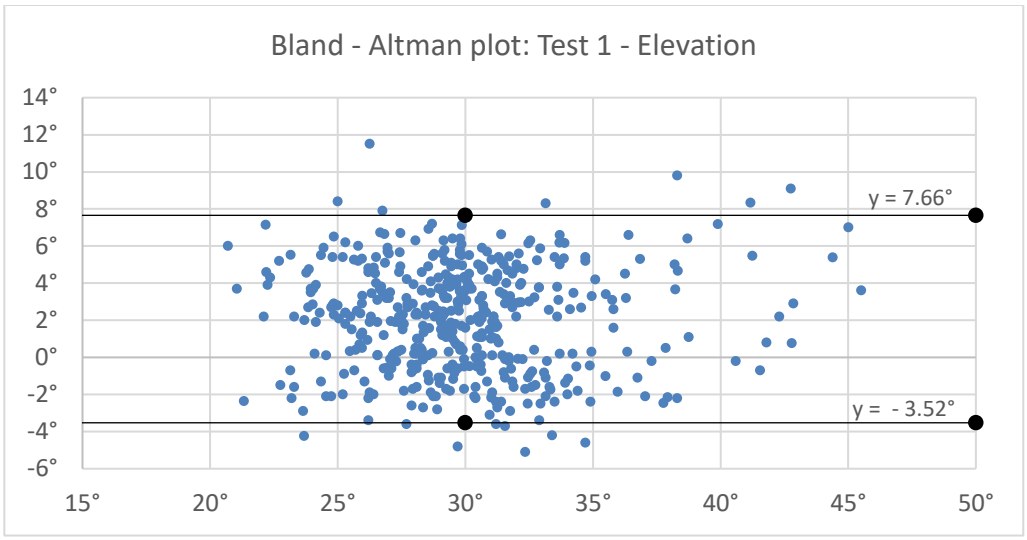


Figure 2-3. An example of chosen cues in the Dartfish Pro software from participant #4 in both planes of "Elevation" (left) and "POE" (right).

Figure 2-4. Test setup prepared for the study including the Job-Sim settings and Go-Pro Cameras



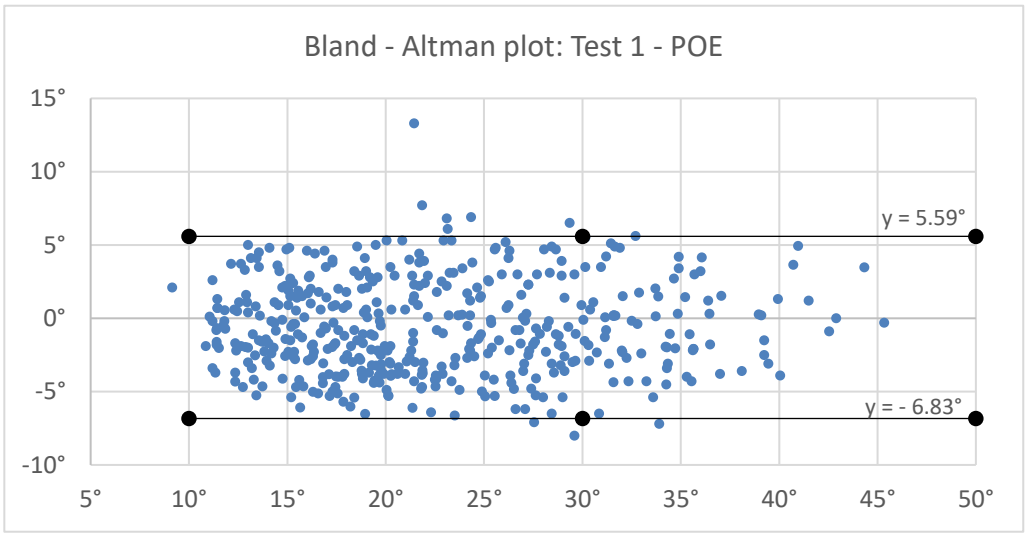


Figure 2-5. The Bland-Altman plots representing the accumulated set of arc of motions obtained from all participants in Task-1 of FIT-HaNSA (number of motions:458); Elevation (Top), POE (Bottom). Lines are representing the upper and lower bounds of Limits of Agreement.

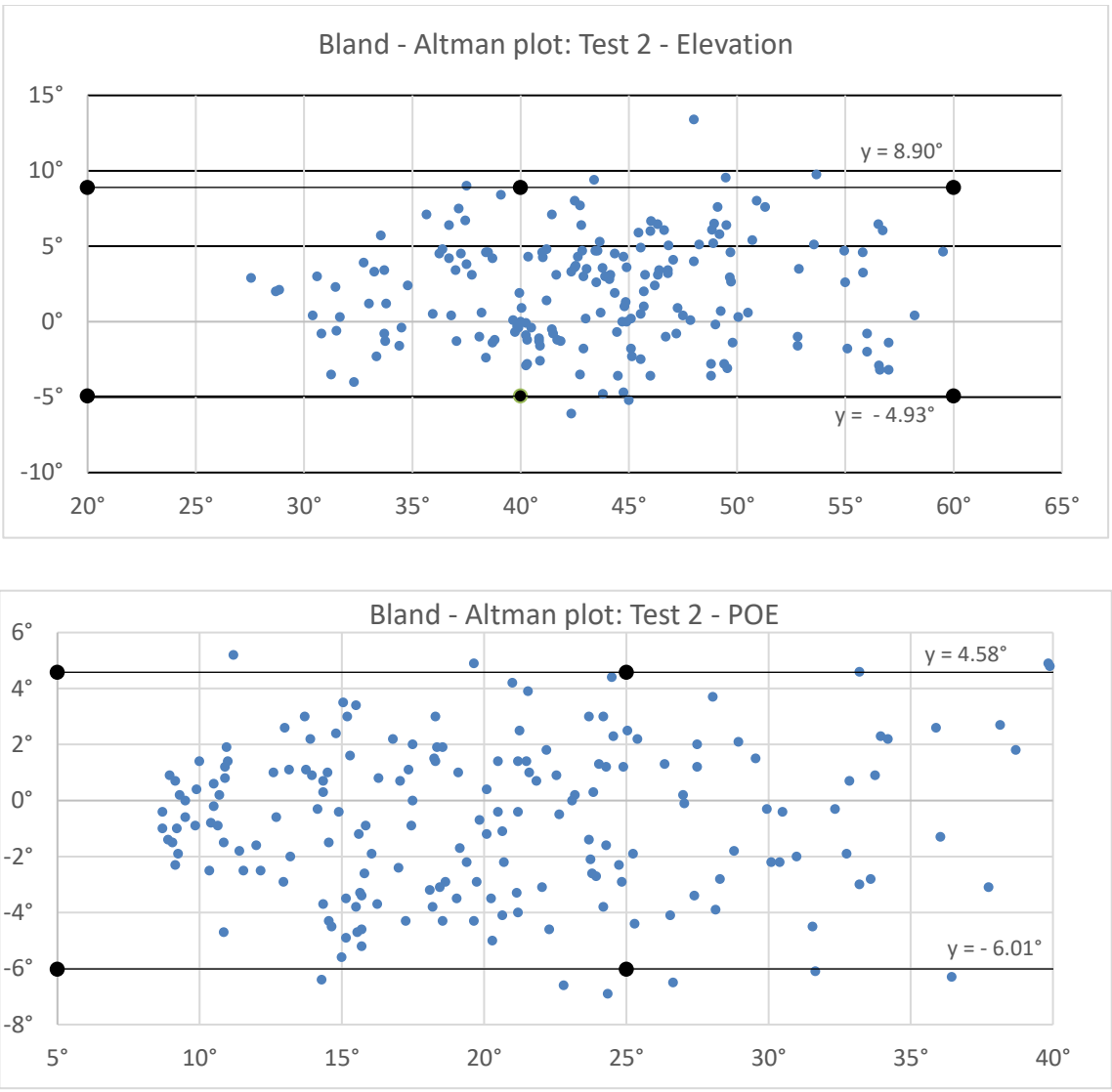


Figure 2-6. The Bland-Altman plots representing the accumulated set of arcs of motions obtained from all participants in Task-2 of FIT-HaNSA (number of motions:184); Elevation (Top), POE (Bottom). Lines are representing the upper and lower bounds of Limits of Agreement.

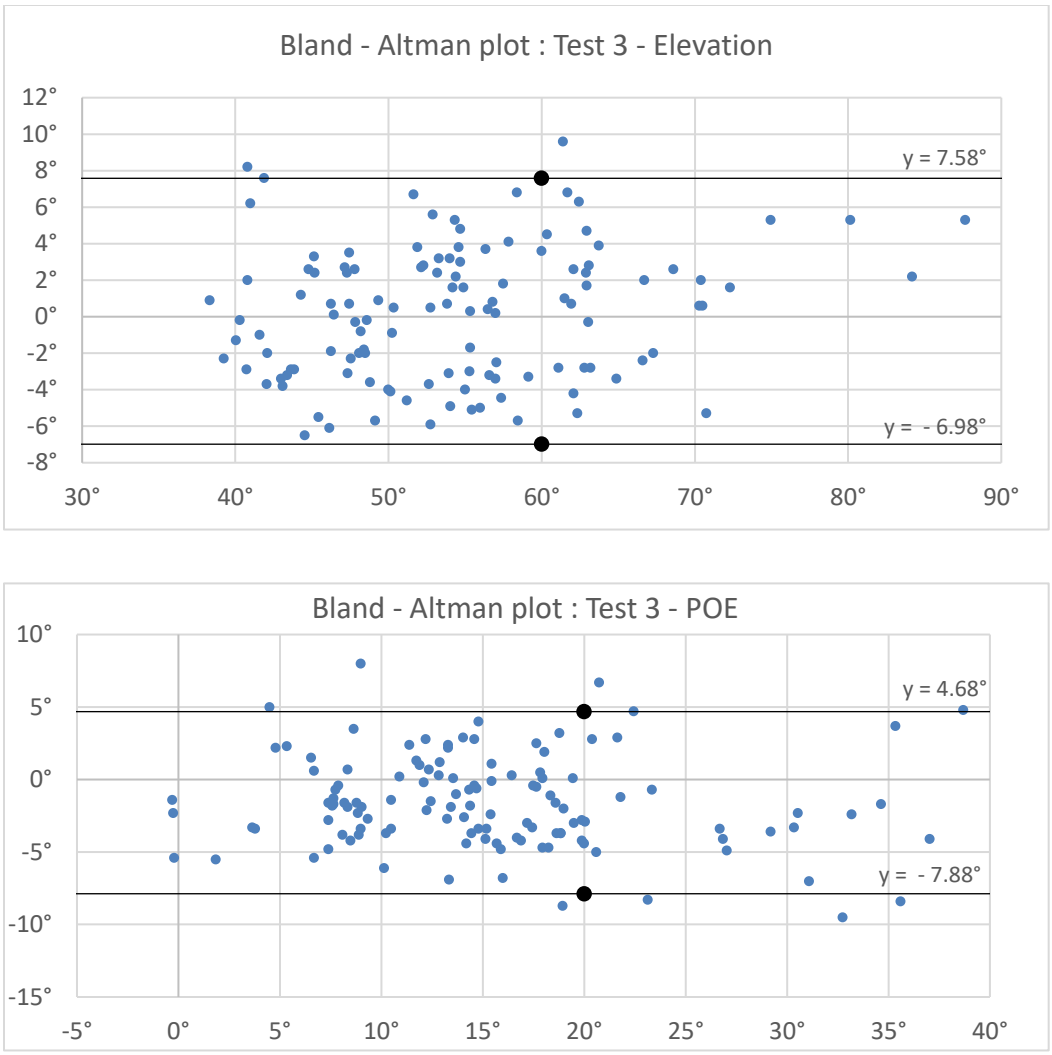


Figure 2-7. The Bland-Altman plots representing the accumulated set of arc of motions obtained from all participants in Task-3 of FIT-HaNSA (number of moves:123); Elevation (Top), POE (Bottom). Lines are representing the upper and lower bounds of Limits of Agreement.

Chapter 3

3 Assessing the Inter-trial reliability of the Shoulder Range of Motion Measurement Using a Wearable Motion Tracking System, "Motion Shirt"

This study has been submitted to Sensors Journal.

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Abstract

Background and aim: This study assessed inter-trial reliability of range of motion (ROM) indicators collected by a custom "Motion Shirt," with wearable embedded Inertial Measurement Units (IMUs) strategically positioned to measure shoulder angular movements during the FIT-HaNSA test.

Methods: A prospective study was conducted with 13 participants awaiting shoulder replacement surgery, utilizing the Motion Shirt during the FIT-HaNSA test. Inter-trial reliability was evaluated through measuring the Intraclass Correlation Coefficients (ICC) for recorded angles of elevation and plane of elevation in three endurance-based tasks of the FIT-HaNSA test. The FIT-HaNSA tasks involved picking up/dropping off objects from shelves at two different heights and screwing bolts in an overhead position. The ICC was calculated between two subsets of performed motions (the odd- and even-numbered motion sets; Subset 1: Sets 1, 3, 5, etc.; Subset 2: Sets 2, 4, 6, etc.) in each task of the FIT-HaNSA test. We used one sample t-test to test the statistical significance of the differences between the two subsets of measurements being compared.

Results: The Motion Shirt demonstrated good to excellent inter-trial reliability with an average ICC ranging from 0.67-0.78, in measuring shoulder movements across task-1 and task-2 sets of the FIT-HaNSA test across both elevation and plane of elevation axes. In task-3, Motion Shirt showed an excellent inter-trial reliability with an average ICC of 0.97 and 0.89 across elevation and plane of elevation axes, respectively.

Conclusion: The study highlights the Motion Shirt's commendable inter-trial reliability in assessing shoulder ROM through the standardized context of the FIT-HaNSA test, with the task-1 and task-2 showing potential challenges related to compensatory movements.

3.1 Introduction

Innovative mobility-tracking technologies may provide an accurate assessment of treatment intervention outcomes. In this context, wearable sensor technology, particularly Inertial Measurement Unit (IMU) sensors, have emerged as potentially feasible and accurate methods for evaluating joint motion and movement patterns [39,43,65–68]. IMU-based wearable systems have proven to be reliable in capturing shoulder movements in healthy participants and patients [21,69,70].

Technological advances have unveiled a myriad of possibilities, and IMU sensors, with their objectivity, affordability, and portable design, are at the forefront of this revolution. Recent studies exploring the applications of IMU-based wearable sensors showcase their validity and reliability in capturing human movement dynamics [27,33,34,59,60].

Previous studies have measured the reliability of using IMU sensors for tracking shoulder range of motion in healthy participants [28,71]. The reliability of the RSQ Motion sensor was assessed in a study to measure the active range of motion (ROM) of the shoulder. Fifteen asymptomatic volunteers participated in the study and underwent testing of flexion, abduction, external and internal rotation. Results demonstrated a good level of agreement (ICC 0.7–0.88, Limits Of Agreement 22–37 degrees) for intra-rater reliability [19]. Another study focused on enhancing the clinical assessment of shoulder function in brachial plexus birth injury (BPBI) by integrating a wearable inertial movement unit (IMU) system with the commonly used modified Mallet scale (MMS). The MMS, while widely used for grading shoulder function in BPBI, exhibits limitations in sensitivity, particularly for scapulothoracic and glenohumeral mobility. The study evaluated reliability in both asymptomatic individuals and BPBI patients via placing IMUs on the upper arm, forearm, scapula, and thorax, and recording peak angles, range of motion, and average joint angular speed during mobility assessments and MMS tasks. Intraclass correlation coefficients demonstrated good-to-excellent test–retest reliability for 90.3% of the 69 outcome scores, with 41% showing significant differences between BPBI patients and controls [72]. Passive shoulder positions were also measured and tested for reliability using an IMU-based system in healthy participants [73]

As demonstrated in our earlier study, embedded with five IMUs strategically positioned on a flexible garment, the “Motion Shirt” provides continuous measurement of shoulder angular movements. Our findings showcased motion shirt's concurrent validity for range of motion analysis in patients awaiting shoulder replacement surgery by comparing the recorded IMU motion data with the ROM measurements obtained through Dartfish video. The study supported the use of the “motion shirt” and IMU sensors for broader applications in the assessment of shoulder function and rehabilitation. While our previous study has successfully demonstrated the validity of the "Motion Shirt" in accurately measuring shoulder angular movements, there remains a notable absence of research investigating the internal consistency of these measurements.

Specifically, we seek to determine whether the recorded measurements remain consistent over time and under varying conditions like pre-surgical status of the shoulder.

Hence, the aim of this study was to assess the inter-trial reliability of the shoulder range of motion measurements obtained using the IMU enabled Motion Shirt during three tasks of the FIT-HaNSA test. Obtaining reliable measurements with the wearable system across two axes—elevation and plane of elevation—within the motion sets of the FIT-HaNSA test, which involves repetitive object pick-up and placement at two different heights, as well as repetitive fastening and unfastening of bolts [53], is crucial for adapting the Motion Shirt for clinical practice. The FIT-HaNSA test simulates three daily life activities of picking up and dropping off objects from two different heights and an overhead sustained activity of (un)fastening bolts. The collected motion data during performing these tasks yields new insights for rehabilitation and clinical applications.

3.2 Methods

In this prospective study, we explored the internal consistency of the ROM measurements captured by the Motion Shirt while performing the Fit-HaNSA test. Our study has been approved by our institutional ethics committee (LHRI# 121356) prior to the commencement of data collection.

Between February 2023 and June 2023, participants meeting specific criteria were enrolled: inclusion criteria were adults aged 50 or above, on the waiting list for shoulder replacement surgery, and proficient in English for test and intervention understanding; exclusion criteria were severe medical conditions such as neurological disorders or motion limitations hindering participation in the Fit-HaNSA test and daily activities.

3.2.1 Study Procedure:

For recruiting the participants of the study, patients were approached during their pre-operative clinic visit to be informed about the study. Upon expressing interest, the study protocol and procedures were explained to them and then they were provided with written letter of information and consent forms to be filled. After obtaining consent, patients were invited to the research lab, where they were introduced to the test situation, fitted with the Motion Shirt, and guided through the Fit-HaNSA test. Patient demographic information, including age, sex, and shoulder pathology, was gathered during the baseline assessment.

The duration of the test varied, lasting approximately 15-30 minutes depending on the individual patient's physical condition and tolerance. Participants received specific instructions for each task based on the research protocol. IMU sensors were securely placed in sewn pockets, and the JobSim device (JTech Medical, Salt Lake City, USA) settings, a task simulator, were configured for each task [62]. Participants started in a "tin soldier" position, defined as 0° of abduction and 0° of internal-external rotation. The FIT-HaNSA test protocol proposed by Kumta et al. [62], with defined the rest periods and maximum duration of each task was utilized. After completing each task, sensors were deactivated during rest periods while settings for the next task were prepared. Once all tasks were completed, the sensor data were downloaded and analyzed, with the duration of each Fit-HaNSA task recorded.

3.2.2 Wearable Sensor System:

The Motion Shirt, as a developed instrument by Langohr et al.[60], is a flexible, long-sleeved garment embedded with five Inertial Measurement Units (IMUs), to measure and monitor shoulder motions in the upper extremities. The IMUs were strategically placed at specific anatomical points: near the sternum to track torso orientation, two on each arm at the mid-humerus for humeral orientation, and two on the dorsal side of each wrist for forearm orientation. To ensure data integrity, all IMUs can store orientation data on micro-SD cards.

3.2.3 FIT-HaNSA Test:

The FIT-HaNSA is a reliable and valid assessment of impaired functional performance in patients with shoulder pathology. It consists of three tasks simulating daily activities of lifting and sustained overhead work in the household or workplace [53,62]. Task 1 involves repetitive reaching and lifting of three 1 kg jars from a waist height shelf to a second shelf that was 25 cm higher and then returning the jars to their initial position. Task 2 is a similar repetitive reaching task that involves lifting the three 1 kg jars from a shelf positioned 25 cm below the participant’s eye level to a second shelf at the participant’s eye level and then returning the jars to their initial position. The participant lifts jars at a standard speed of 60 beats per minute (a metronome is used to keep the pace for the participants). Task 3 simulates sustained overhead activity by repetitive fastening and unfastening of bolts into three threaded holes in a metal attachment plate. Participant safety was prioritized, and the task continued for a maximum duration of 300 seconds or until the participant

indicated pain or fatigue. The elapsed time and shoulder angle recording assessment of each participant's performance was recorded. In the present study, we have considered Task 1 and Task 2 as motion sets each comprised of 6 distinctive motions (one pick up and one drop off motions for each 3 jars). Task 3 involves 2 distinctive fastening and unfastening motions for each specified hole. Since there are three designated holes on the plate; therefore, each set in Task 3 includes 3 motions.

3.2.4 Data analysis:

The IMU sensors within the "motion shirt" measured the instantaneous angle at each time sample (0.1 seconds). By analyzing the angles formed between the sensors, shoulder joint angle is determined across two axes: Elevation and Plane of Elevation (POE). The Elevation and POE axes as specified by Langohr et al. [60], are presented in Figure-2. To estimate the angle range of the motions performed during the test, we calculated the arc of motion, which represents the total angular difference in both axes between the picking and dropping moments for the three objects used in Tasks 1 and 2 of the FIT-HaNSA test. In Task 1 and Task 2, the arc of motion for each performed pick up or drop off motion is calculated and recorded across both axes. In summary, elevation and POE planes are defined the vertical and horizontal angular arc of shoulder motion, respectively.

In Task 3, the constant angles of the humerus during the process of fastening and unfastening bolts at each 3 different holes in both elevation and the plane of elevation were measured for each fasten/unfasten motion. Additionally, the mean and standard deviation (SD) of the recorded arcs of motion for each participant were calculated in all three tasks.

In the data preparation phase for calculating the Intraclass Correlation Coefficient (ICC), we organized the tasks into two distinct groups. our approach involved grouping all three tasks into sets based on odd and even numbering. It must be mentioned that unfinished sets of motions were removed from analysis process to maintain the integrity of results in our approach. Moreover, the mean and the Minimum Detectable Change (MDC) values of Odd-numbered and Even-numbered sets for each participant has been calculated.

3.2.5 Statistical tests:

Continuous variables were reported as the mean (standard deviation) and categorical variables are reported as the absolute amounts (percentage). We used Shapiro-Wilk test to check the normality assumption of our data.

We calculated and reported two-way random effects model ICC (2,1) [74] via both approaches (odd/even sets and pickup/drop moves) for elevation and plane of elevation separately for all three tasks, where both people effects and measures effects are random. We also calculated minimum detectable change (MDC) and mean arc of motion values in both even- and odd-numbered sets of each participant. The Intraclass Correlation Coefficient (ICC) values below 0.4 suggest poor reliability, those between 0.4 and 0.75 indicate moderate (fair to good) reliability, values exceeding 0.75 suggest excellent reliability [75].

As the primary objective of our study is to assess the reliability of the Motion Shirt, it is imperative to conduct reliability assessments under conditions of participant stability, uncontaminated by variables such as fatigue. Given that the FIT-HaNSA test, utilized herein, is stopped upon participant fatigue, we have omitted the final motion set of each participant from the calculation of the Intraclass Correlation Coefficient (ICC). This methodological approach ensures the accuracy and validity of ICC values by minimizing the influence of participant fatigue and discomfort on the reliability assessment.

Furthermore, we used a one sample t-test to test the statistical significance of the differences between the two odd- and even-numbered subsets being compared. A p-value < 0.05 indicated the level of significance for all analyses. Statistical analysis was performed using IBM SPSS Statistics 29.

3.3 Results

A total of 13 participants (8 male, 5 female) completed the test. The mean age was 66.5 (±8.1). Most of the participants (88%) were scheduled for shoulder surgery (either total or reverse shoulder joint replacement) on their dominant side. The majority of the participants (79%) completed at least three sets of each task of the Fit-HaNSA.

In the following, we have calculated and reported ICC values separated by the tasks of the FIT-HaNSA test for each participant's individual performance. The blank rows pertain to participants who performed fewer than 2 sets of motions. (Table-2, Table-3, and Table-4).

The results of angle measurements separated in even/odd sets for Task 1 has been presented in Table-2. Also, the number of performed sets by each participant is included. It must be noted that for participants performing motions below 2 sets, ICC values could not be calculated, as the minimum number of even-numbered and odd-numbered sets were not available.

According to Table-2, the mean(SD) ICC values for the performed motions of all participants in Task 1 are 0.72(0.1) and 0.77(0.1) for Elevation and POE, respectively. Moreover, the average recorded arcs of motion in odd- and even-numbered sets in Elevation are 29.5° and 28.9°, respectively, and for POE are 23.2° and 23.8°, respectively, representing a difference of less than 1°. The Minimum Detectable Change also shows an average of 3° and 3.1° in odd- and even-numbered sets across the Elevation axis, and 4.2° and 4.6° across the POE axis, respectively. The Minimal Detectable Change (MDC) was computed to assess the sensitivity of the Motion Shirt in detecting clinically significant changes in shoulder and arm movements. The MDC was calculated using the standard deviation (SD) of repeated measures obtained from the Motion Shirt ($MDC=1.96\times SD\times 2$). This computation ensures that any observed changes in motion exceed the inherent variability of the measurement system, thereby reflecting true changes in patient performance. The MDC is critical for distinguishing between measurement error and real clinical improvements.

The mean(SD) ICC values for the participants' arm elevation and POE during Task 2 were 0.67(0.1) and 0.78(0.1) respectively, indicating a good to excellent reliability. Furthermore, the average angles of motion recorded in odd- and even-numbered sets for Elevation are 42.9° and 43.3°, respectively, while for POE, they are 21.5° and 22.3°, respectively, demonstrating a difference of less than 1° between the two sets. Additionally, the Minimum Detectable Change reveals an average of 4.6° and 4° for odd- and even-numbered sets across the Elevation axis, and 4.8° and 6.2° across the POE axis, respectively. Table-3 summarizes the findings for Task 2.

Table-4 presents the mean(SD) ICC values for the motions performed by all participants in Task 3. These values were 0.97(0.04) and 0.89(0.1) for Elevation and POE, respectively, suggesting an

excellent reliability of the Motion Shirt measurements in Task 3 of the FIT-Hansa test. Moreover, the average recorded angles in odd- and even-numbered sets were similar for Elevation (53.6°) and POE (108.9°) were similar for both sets. Task-3 represents a consistent standing and endurance-based motion, and the arc of motion data does not highlight any significant information. Therefore, the constant angles are recorded to show the stance of participants during an overhead activity of fastening and unfastening bolts. The Minimum Detectable Change in Task 3 was 7.3° and 8.3° for odd- and even-numbered sets across the Elevation axis, and 5.1° and 5.9° across the POE axis, respectively.

The results of the t-test analysis in all three tasks supported the ICC findings and the p-value for none of the abovementioned movements was statistically significant.

3.4 Discussion

We evaluated the internal consistency of Motion Shirt measurements through comparing the arcs of motions in two subsets of collected data in each partiicpants. The Intraclass Correlation Coefficient (ICC) values for the Elevation axis motion shirt measurements for Tasks 1 and 2 demonstrated good inter-trial reliability with mean values of 0.72 and 0.67 respectively. In POE axis, excellent mean ICC values of 0.77 and 0.78 for Tasks 1 and 2, respectively were obtained. The Task-3 ICC scores for elevation and POE were 0.97, and 0.89, respectively, demonstrating an excellent reliability of motion shirt measurements for task-3. These results indicate the good to excellent inter-trial reliability and consistency of the motion shirt's shoulder motion measurements during the Fit-Hansa Test.

Our findings from a cohort of 13 participants awaiting shoulder replacement surgery, underscore the Motion Shirt's commendable inter-trial reliability in recording the arcs of motions of shoulder joint across two different axes. Most participants could complete at least three sets of each FIT-HaNSA task and use of the Motion Shirt in a clinical setting should be feasible. The variability in number of performed sets, participant discontinuation due to pain or functional limitations, and the variance in angles within individual performances (that may be attributed to the compensatory strategies shown by some participants due to their condition) may account for the absence of excellent reliability (ICCs > 0.75) in the elevation axis of Tasks 1 and 2 results. However, the

obtained ICC values are close to the 0.75 threshold. These findings underscore the real-world challenges and diverse patient experiences encountered during patient assessment.

Another potential reason for observing a good level of reliability in the Elevation axis of Task 1 and Task 2, can be attributed to the limited quantity of data points available. Among the 13 participants engaged in Task 1, it was noted that 3 individuals demonstrated a performance level above 30 motions (5 sets). Similarly, in both Task 2 and Task 3, only one of the participants executed more than 30 motions.

The consistency and reliability observed in the plane of elevation recordings were expected since the movements in the horizontal plane typically involve a narrower range of angles compared to those in the elevation axis, as seen in both Task 1 and Task 2. Specifically, the mean values of the arcs of motion for even and odd sets in the plane of elevation axis are lower than the mean arcs of motion values in the elevation axis. The observed variances in ICC values related to participants' performances in Tasks 1 and 2, prompts a closer examination of the intricacies involved in these tasks. The requirement for participants to pick up a jar from a lower level and subsequently drop it off on a higher level introduces a unique set of challenges that may lead to compensatory movements. In Task 1, the necessity for participants to engage in a vertical movement from a lower to a higher level inherently requires coordination between the shoulder and trunk. The potential for compensatory trunk movements arises as individuals seek to navigate this specific spatial challenge. Such compensatory actions may manifest as alterations in torso orientation, which, while aiding in the completion of the task, could introduce variability in the Motion Shirt's collected data in the study. However, the motion shirt is still effective to consistently capture the intended shoulder range of motion.

These compensatory movements, while natural adaptations to the task's demands, may contribute to the observed inconsistencies in the Motion Shirt's recordings during Tasks 1 and 2. Consequently, these results highlight the importance of considering task-specific challenges and potential compensations when interpreting wearable sensor data. It emphasizes the need for a nuanced understanding of how individuals adapt their movements, especially in scenarios where the task design may encourage compensatory actions.

Addressing these complexities becomes crucial not only for refining the Motion Shirt's application in clinical assessments but also for providing insights into the broader implications of compensatory movements in functional tasks. Future research endeavors could delve deeper into understanding the nature of compensatory trunk movements during tasks, shedding light on how wearable technologies can be optimized to accurately capture shoulder range of motion in the presence of such compensations.

On the contrary to the motions in Task 1 and Task 2, the excellent reliability observed in Task 3, despite its smaller number of motions and sets, can be attributed to the nature of the motions required for this task. These motions are more stationary and involve a narrower frequency of movements when compared to those in Task 1 and Task 2. For instance, the actions of fastening and unfastening bolts do not entail a wide range of shoulder movement. Therefore, it is expected that in tasks involving more stationary movements, the Motion Shirt may exhibit greater reliability levels.

The Minimum Detectable Change (MDC) is an indicator of measurement error relative to the range of motion performed across all three tasks. These values range from 3° to 8.3° across the Elevation axis and from 4.2° to 6.2° across the Plane of Elevation (POE) axis, which aligns with findings from studies by Beshara et al. and Kaszyński et al. [19,76]. Notably, the MDC ranges increase from Task 1 to Task 3 in the Elevation axis, reflecting the wider ranges of motion required to perform these tasks. Overall, these small measurement errors underscore the Motion Shirt's ability to accurately capture true changes in participants' shoulder motion for values above this range.

The internal consistency of measurements obtained with wearable motion tracking systems is interesting. Several studies have investigated the reliability (internal consistency) of IMUs in capturing joint movements. In a study by Camp et al., excellent internal consistency in shoulder rotation (excellent reliability with <5° of error; percentage difference with the gold standard of marker-based motion capture, 0.5%-1.6%) was found for IMU sensors in a total of 10 healthy male baseball athletes [77]. In a systematic review by Poitras et al. in 2019, the authors assessed the reliability and validity of the wearable sensors for joint angle estimation. The ICC values for the shoulder measurements ranged from 0.71 to 0.99. The authors found higher reliability values for flexion/extension movements than abduction/adduction and rotational movements [78]. Furthermore,

the reliability and consistency of the IMU measurements have been assessed in several other joints, including neck, trunk, lower limb joints [78] and body movements/conditions and movement analysis, such as gait analysis [79,80], swimming [81], or neurological disease [37]. IMU measurements demonstrated acceptable/excellent reliability and consistency in the findings.

Our data analysis phase reflects a methodological consideration to comprehensively understand the Motion Shirt's performance across various task categories. The statistical significance derived from one sample t-tests adds a layer of consistency to the study, reinforcing the reliability of the Motion Shirt in comparison to established measures.

These results enhance considerations for the Motion Shirt's integration into clinical practice and research settings. The system's ability to consistently measure shoulder movements, as validated by our study, positions it as a valuable tool for clinicians and researchers alike. The Motion Shirt's strategic placement of IMUs across specific anatomical points ensures a comprehensive evaluation of torso, humeral, and forearm orientations, contributing to a holistic understanding of shoulder motion.

While our study highlights the promising reliability of the Motion Shirt, certain limitations must be acknowledged. The small sample size, the condition of patients that might impacted the number of performed motions, and the specific demographic of participants awaiting shoulder replacement surgery may limit the generalizability of our findings to a broader population. Additionally, the challenges encountered during the FIT-HaNSA test, leading to variable completion times and participant cessation, underscore the importance of adapting wearable technologies to diverse patient conditions.

The findings of this study align seamlessly with and further substantiate the conclusions drawn in Chapter 2, where we initially established the validity of the Motion Shirt in recording the shoulder motions for the same population of the present study. The reaffirmation of the Motion Shirt's reliability across varied movements during the FIT-HaNSA test serves to fortify and extend the foundation laid by our preceding research. This cohesive narrative not only underscores the repeatability and accuracy of the Motion Shirt but also reinforces its potential as a dependable tool for comprehensive shoulder motion assessments in clinical and research settings.

3.5 Conclusion

This study shows a novel wearable sensor system called Motion Shirt demonstrates a good to excellent reliability and consistency in assessing shoulder range of motion during the FIT-HaNSA test on patients prior to their Shoulder-joint replacement surgery. The findings indicate that Motion Shirt can be a reliable tool in objective and continuous clinical assessment of patients and presents a great potential to be used for remote recovery monitoring process. The results of the present study pave the way for continued research and potential applications of the Motion Shirt in enhancing the precision and efficiency of shoulder joint function assessments, ultimately contributing to improved postoperative rehabilitation and surgical outcomes for individuals awaiting shoulder replacement surgery.

3.6 List of Tables

Table 3-1. Baseline Characteristics of study's participants (n=13)

Age(mean±SD), y	66.5±8.1
Sex, n	
Males	8 (62%)
Females	5 (38%)
Side tested for the FIT-HaNSA, n	
Right	8
Left	5

Table 3-2. ICC, Mean, and MDC Values for Odd- and Even-Numbered Sets of Motions in FIT-HANSA Task 1, Across Two Planes of Elevation and the Plane of Elevation (POE).

	Elevation						POE				
PARTICIPANT ID	N Sets	ICC	Mean Odd (°)	Mean Even (°)	MDC Odd (°)	MDC Even (°)	ICC	Mean Odd (°)	Mean Even (°)	MDC Odd (°)	MDC Even (°)
#1	4	0.83	26.0	24.0	3.7	3.2	0.76	21.8	23.9	3.9	3.8
#2	3	0.52	35.0	34.5	4.1	3.7	0.80	34.0	35.6	3.0	4.2
#3	2	0.84	27.9	28.0	4.1	3.0	0.68	19.1	21.4	7.9	8.3
#4	21	0.65	29.3	28.9	1.1	1.1	0.77	22.6	21.0	2.4	2.2
#5	4	0.61	32.5	32.4	4.7	8.1.	0.79	29.2	27.2	4.7	5.0
#6	5	0.6	28.9	28.1	2.3	2.0	0.73	22.7	25.1	3.0	5.5
#7	0	-					-				
#8	6	0.83	26.5	28.1	2.7	1.7	0.80	20.3	21.0	4.6	5.6
#9	5	0.87	29.3	30.2	2.2	2.8	0.78	32.9	29.5	4.4	5.4
#10	8	0.60	27.9	27.1	1.9	1.8	0.77	21.8	22.8	3.2	3.5
#11	2	0.64	28.1	24.2	4.0	3.4	0.68	19.9	23.0	4.2	3.8
#12	12	0.68	28.1	27.3	1.1	1.1	0.94	17.4	18.0	2.9	2.9
#13	2	0.98	33.9	33.8	4.5	5.1	0.83	17.2	16.7	5.9	4.7
MEAN(SD)		**0.72 (0.1)**	**29.5**	**28.9**	**3.0**	**3.1**	**0.77 (0.1)**	**23.2**	**23.8**	**4.2**	**4.6**

Table 3-3. ICC, Mean, and MDC Values for Odd- and Even-Numbered Sets of Motions in FIT-HANSA Task 2, Across Two Planes of Elevation and the Plane of Elevation (POE).

		Elevation					POE				
PARTICIPANT ID	N sets	ICC	Mean Odd (°)	Mean Even (°)	MDC Odd (°)	MDC Even (°)	ICC	Mean Odd (°)	Mean Even (°)	MDC Odd (°)	MDC Even (°)
#1	0	-					-				
#2	2	0.59	45.8	45.3	5.8	2.3	0.74	22.3	23.3	7.2	11.8
#3	1	-					-				
#4	4	0.61	43.5	41.2	3.8	2.6	0.73	26.4	26.6	3.0	4.8
#5	1	-					-				
#6	3	0.62	39.6	39.3	5.1	3.5	0.78	18.8	22.2	4.7	7.5
#7	0	-					-				
#8	3	0.52	38.2	40.8	3.9	5.3	0.68	20.2	22.4	6.7	8.8
#9	3	0.62	46.2	43.7	5.4	6.4	0.79	27.5	29.7	6.2	6.2
#10	4	0.84	48.8	52.4	4.4	4.0	0.85	23.1	20.0	4.2	2.5
#11	0	-					-				
#12	7	0.88	38.3	40.2	3.7	3.7	0.89	12.4	12.0	1.8	1.7
#13	2	-					-				
MEAN		**0.67 (0.1)**	**42.9**	**43.3**	**4.6**	**4.0**	**0.78 (0.1)**	**21.5**	**22.3**	**4.8**	**6.2**

Table 3-4. ICC, Mean, and MDC Values for Odd- and Even-Numbered Sets of Motions in FIT-HANSA Task 3, Across Two Planes of Elevation and the Plane of Elevation (POE).

		Elevation					POE				
PARTICIPANT ID	N Sets	ICC	Mean Odd (°)	Mean Even (°)	MDC Odd (°)	MDC Even (°)	ICC	Mean Odd (°)	Mean Even (°)	MDC Odd (°)	MDC Even (°)
#1	1	-					-				
#2	0	-					-				
#3	3	0.99	54.5	51.1	10.7	7.5	0.94	104.9	103.4	3.4	4.1
#4	12	0.89	48.3	49.6	4.2	3.7	0.93	104.6	104.6	2.9	2.7
#5	0	-					-				
#6	5	0.99	63.7	63.1	5.1	6.7	0.69	100.8	99.4	3.2	2.9
#7	0	-					-				
#8	1	-					-				
#9	4	0.97	54.4	53.1	8.6	8.2	0.86	118.6	118.7	5.9	10.1
#10	3	0.97	48.5	51.0	11.0	19.1	0.92	115.7	119.4	12.7	13.4
#11	2	-					-				
#12	6	0.97	52.4	53.8	4.1	4.3	0.97	109.0	107.6	2.2	2.4
#13	1	-					-				
MEAN		**0.97 (0.04)**	**53.6**	**53.6**	**7.3**	**8.3**	**0.89 (0.1)**	**108.9**	**108.9**	**5.1**	**5.9**

3.7 List of Figures

Figure 3-1. The study's test arrangement, encompassing the Job-Sim settings

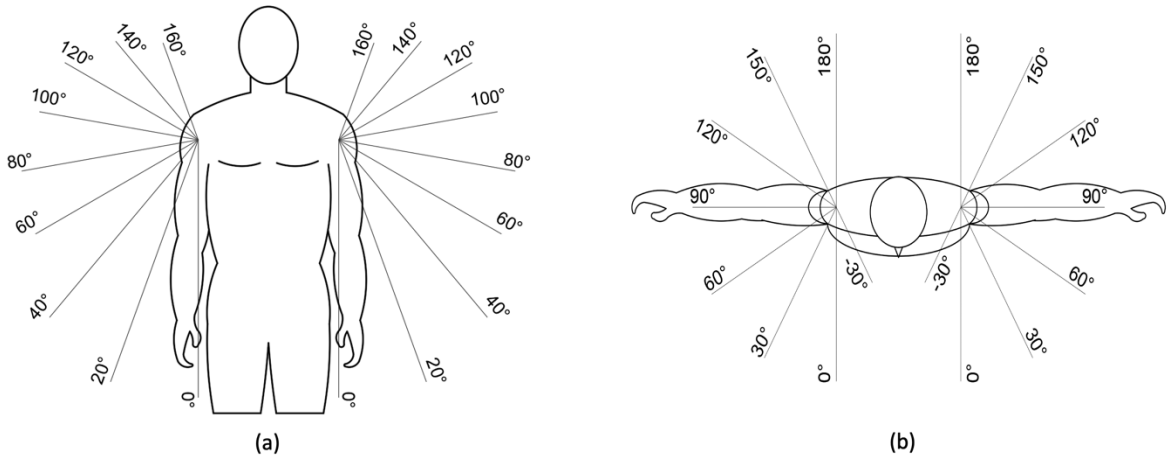

Figure 3-2. The specified "Elevation" (a) and "Plane of Elevation" (b) as per Langohr et al., 2018.

Chapter 4

4 Assessment of Shoulder Joint Replacement Patients' Motion Outcomes Using a Wearable Sensor System, Motion Shirt: A Six-Month Post-Surgery Evaluation

This study has been submitted to Biomedical Physics & Engineering Express Journal.

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Abstract

Aim/Background: The present study assessed the functional skills and motion outcomes of patients undergoing shoulder joint replacement (SJR) surgery including both anatomic and reverse shoulder arthroplasty, using a pre-validated wearable sensor system called, the "Motion Shirt". Our aim was to evaluate preoperative and 6-month post-operative shoulder motion measures to identify statistically significant motion outcome improvements.

Methods: The motion data was collected using the Motion Shirt to compare the shoulder joint angles before and after surgery. The study was conducted on patients in the waiting list of SJR surgery. Pre- and post-operative standardized activities concentrating on shoulder motions in two planes—elevation and plane of elevation (POE)—were administered based on the Functional Impairment Test-Hand and Neck/Shoulder/Arm (FIT-HaNSA), a standard test with three separate tasks. Motion outcomes such as number of motions, arcs of motion (AoM), elapsed time, promptness, and workload of 15 participants (mean age = 66.6) during the FIT-HaNSA test before the surgery and 6-month post-surgical rehabilitation were collected and compared to find meaningful differences.

Results: In Task 1 of the FIT-HaNSA test, participants averaged 25.1 moves (SD=18.1) before surgery as opposed to 33 pickup/drop off moves (SD=14.2) after the surgery (p-value=0.02; Effect Size = 0.5). Similar improvements were observed in Task 2, when subjects completed an average of 13.5 moves (SD=12.6) prior to the surgery as opposed to 20 pickup/drop off moves (SD=7.3) after the surgery (p-value=0.045; Effect Size = 0.6). In Task-3, a significant increase was also measured as participants demonstrated an average of 6.9 moves (SD= 4.7) prior to the surgery compared to an average of 9.4 fasten/unfasten bolt moves (SD= 2.4) after the surgery (p-value= 0.03; Effect Size = 0.7). Motion promptness in the Elevation axis showed a significant increase in Task-1 (p-value<0.001; Effect Size = 0.8), Task-2 (p-value=0.008; Effect Size = 1.2) and Task-3 (p-value= 0.02; Effect Size = 0.6). In Task 2, a significant improvement was measured in mean arc of motion (AoM) in the Elevation axis, with an average AoM increasing from 41.6° (SD=4.9) pre-surgery to 45.7° (SD=5.6) post-surgery (p-value=0.007; Effect Size = 0.8). Promptness across POE axis also significantly improved in Task 3 (p-value=0.02; Effect Size = 0.6). However, no

significant differences were found between the pre- and 6-month post-surgery timepoints regarding the elapsed time and the workload in all three Tasks of the FIT-HaNSA test.

Conclusion: Six months after shoulder joint replacement (SJR), patients showed significant improvements in the number of movements in Task 1, Task 2, and Task 3 of the standardized FIT-HaNSA test, compared to their preoperative scores. Additionally, the promptness of motion across the elevation axis improved for all tasks. These results suggest a marked enhancement in functional motion outcomes after a 6-month rehabilitation period following SJR surgery.

4.1 Introduction

Patients with severe shoulder arthritis or other debilitating shoulder conditions often undergo shoulder joint replacement (SJR) surgery, also known as shoulder arthroplasty. This standard orthopedic procedure aims to relieve pain and improve function in patients dealing with shoulder conditions [82,83]. While this operation can significantly enhance motion and quality of life for many patients, the recovery process and motion outcomes can vary widely among individuals [84,85].

The assessment of shoulder joint motion and performance in patients before and after shoulder joint replacement surgery is helpful for understanding the efficacy of SJR and monitoring patient recovery. Traditionally, patient-reported questionnaires and standardized clinical evaluations using goniometers and inclinometers were employed to evaluate motion outcome measures [86]. However, advancements in wearable sensor technology and Inertial Measurement Unit (IMU) sensors have provided researchers and clinicians with new tools for objective and continuous monitoring of joint motion in real-world settings [34,43,87].

In recent years, researchers have introduced and suggested the use of wearable sensors embedded in flexible garments as a promising and sustainable solution for monitoring joint motion in orthopedic patients. These lightweight electronic devices can capture detailed kinematic data, including joint angles, movement timing, and coordination, during various activities of daily living [88,89]. Therefore, by utilizing these sensors to continuously record joint motions in shoulder joint replacement patients, clinicians and surgeons can gain valuable insights into the effectiveness of the surgery and the rehabilitation process.

The present longitudinal study aimed to utilize wearable sensors embedded in a flexible shirt to assess the change in joint motion following shoulder joint replacement patients comparing pre-surgery and 6-month post-SJR surgery. Specifically, a self-developed previously validated and consistent wearable sensor system called the "Motion Shirt," a flexible garment with five embedded IMU sensors, was worn by patients [60]. Their shoulder joint outcomes were recorded on elevation and plane of elevation (POE) axes during the performance of a standardized functional test called the Functional Impairment Test-Hand and Neck/Shoulder/Arm (FIT-HaNSA) [62]. This endurance test evaluated shoulder function in three different tasks that require varying levels of shoulder activity [62]. We aimed to report key joint metrics such as the minimum, maximum, mean, and standard deviation (SD) of arcs of motion recorded by the Motion Shirt at two different time points (Prior to and 6-month after the SJR surgery). Additionally, we seek to identify differences and improvements in motion outcomes such as the endured time of FIT-HaNSA tasks, shoulder angles, and promptness demonstrated in shoulder joint replacement patients over the six-month postoperative period using statistical analysis. It was hypothesized that overall joint performance metrics and motion outcomes would improve due to a successful 6-month clinical rehabilitation period and the impact of successful SJR surgery on the participants.

4.2 Methods

4.2.1 Study Design

We conducted longitudinal research of consecutive case series on a cohort of patients on the waitlist of shoulder joint replacement surgery in a Hand and Upper Limb Specialty Clinic. Testing was conducted at two different time points (pre-surgery and 6-month post-surgery) in a research laboratory context. The motion data were obtained using the IMUs embedded in the Motion Shirt, and further evaluated by comparing humeral shoulder angles obtained prior the surgery (the test date was not different more than 3 weeks prior to surgery) from with those measured at 6-month post-surgery test day during performing the standardized FIT-HaNSA test using MATLAB (version R2022a, MathWorks Inc., Natick, MA). In accordance with ethical guidelines, institutional ethics board review and approval was obtained prior to commencing the study.

4.2.2 Participants

Participants (n=15) in this study were recruited between February 2023 and February 2024, based on the following inclusion criteria: patients aged 50 or above undergoing shoulder replacement surgery, proficient in English for understanding the tests and interventions. Exclusion criteria included severe medical conditions such as neurological disorders, cardiorespiratory conditions, or mobility limitations preventing participation in the Fit-HaNSA test and daily activities.

4.2.3 Study Procedures

The study was explained to patients during their pre-operative clinic visit. Upon providing written consent to participate in pre- and post-operative test sessions, they were invited to the lab for testing. Test procedures were conducted twice in the lab: once within 3 weeks prior to surgery and then again, at 6 months post-surgery. During the test procedure, shoulder motion was assessed in two planes: "Elevation" and "Plane of Elevation," as specified by Langohr et al. [60]. In this specification, "Elevation" refers to the angular measurement formed by the intersection of the torso and humeral shaft, while the "Plane of Elevation" specifies the direction of humeral elevation, with forward flexion (arm elevated to the front) defined as 0° (Figure 1).

Participants were briefed on the study protocol, the tasks involved in the Fit-HaNSA test, and data usage for motion analysis. They were then fitted with the Motion Shirt, ensuring their comfort before testing. The garment was prepared in various sizes (Small, Medium, Large, etc.), and the appropriate size was selected for each participant. It was also ensured that the shirt fit snugly yet comfortably to accurately secure the IMU sensors in the designated regions. IMU sensors were securely placed in custom-sewn pockets of the Motion Shirt (illustrated in detail in the following section), and the JobSim settings were configured for the FIT-HaNSA test. Participants assumed a "tin soldier" stance, defined as 0° of abduction and 0° of internal-external rotation, with arm motion data recorded upon sensor activation. Sensors were deactivated during rest periods between the FIT-HaNSA tasks while preparations for the next task were made. Upon completion of all three tasks, sensor data were downloaded from the SD memory cards on the sensors and then further analyzed in MATLAB as pre-surgical motion data (Appendix-A), including the elapsed time for each FIT-HaNSA task. This procedure was repeated 6 months post-surgery.

4.2.4 Wearable Sensor System

The Motion Shirt, a developed wearable sensor system by Langohr et al.[60], is a flexible, long-sleeved custom compression garment embedded with five IMU sensors with dimensions of 60 × 35 × 15 mm. The sensors measure different arm angles and shoulder motions of individuals. The IMUs (YEI Technology, Portsmouth, OH, USA) contain triaxial accelerometers, gyroscopes, and magnetometers that provide three-dimensional motion tracking with an accuracy of ±1°. The IMUs were strategically embedded in the following locations: one near the sternum to track torso orientation, two on each arm at the mid-humerus for humeral orientation, and two on the dorsal side of each wrist for forearm orientation. The Motion Shirt was developed to ensure comfort and ease of use for users, allowing continuous, objective tracking of shoulder and arm motions for long periods. Data logging was achieved with a micro SD storage card and data collected during the study was synchronized and transferred to MATLAB for further analysis.

4.2.5 FIT-HaNSA Test

The FIT-HaNSA test is a reliable and valid group of tasks for assessing shoulder-related functional capabilities, which are necessary for monitoring the effectiveness of an intervention or tailoring effective rehabilitation strategies [53]. The test includes three different endurance tasks simulating lifting, dropping, and sustained overhead activities that can be simulated in the lab environment using the JobSim setting (JTech Medical inc., UT, USA) for task staging. The test score is the recorded elapsed time (in seconds) that participants endure during performing each task for a maximum of 300 seconds [53]. Task 1 involves consecutive reaching and placing three 1 kg jars on shelves at waist height on another shelf placed 25 cm above it and then returning them to the initial shelf. Task 2 replicates Task 1 but at eye level and 25 cm below it, and Task 3 involves an overhead sustained activity of repetitive fastening and unfastening of bolts into three threaded holes in a metal attachment plate. Participants must pick up and drop the jars at a standard speed of 60 beats per minute, with all tasks lasting a maximum of 300 seconds or until they feel increasing pain or fall off the 60 beats per minute rhythm, ensuring safety and accurate evaluation of each participant's performance [53].

4.2.6 Data analysis

The collected sensor data at both time points are first imported into a self-developed custom LabView software (National Instruments, Austin, TX), creating a dataset that includes all shoulder angles in the Elevation and Plane of Elevation axes, and elapsed time of each task. Moreover, through visual inspection, any potential missed data, artifacts, or noise is identified. In cases where the data were significantly affected by artifacts, trials were repeated on the same visit on the test site to ensure a clean and reliable data collection process. Subsequently, Motion Shirt sensor data were imported into MATLAB software (version R2022a, MathWorks Inc., Natick, MA), and the arcs of motions recorded during the execution of the FIT-HaNSA tasks were identified and calculated.

The angular difference between the picking moment and dropping moment of the jars used in tasks 1 and 2 of the FIT-HaNSA test were calculated and considered as arcs of motion (AoM). In task 3, the angles of the humerus and torso during fastening and unfastening bolts in both elevation and plane of elevation have been considered and reported for data analysis, as the arc of motion might not include significant clinical information. The mean and standard deviation (SD) of recorded arcs of motion for each participant were also calculated. Minimum and maximum demonstrated angles, number of moves, sets, and elapsed time for each task were also recorded.

Aside from these metrics, the concept of promptness (as an indicator of movement efficiency) was introduced to check if the SJR surgeries might affect the agility of participants in moving their arms. In this regard, the average *promptness* of participants for each task was calculated based on multiplying the number of performed moves and mean shoulder angle in both axes divided by the elapsed time. Moreover, *the normalized workload* was defined and calculated by multiplying the number of performed moves and mean shoulder angle in both axes and the elapsed time of FIT-HaNSA tasks. To avoid reporting large values, the metric is reported as a normalized metric (valued between zero and one). By looking at the smallest and largest values of the metric, a range was obtained. Then, for each value, we figured out where it sits between that smallest and largest point. By doing this, every value is turned into a fraction of the total range. All mentioned metrics were collected for each participant at pre- and post-surgical time points to be compared with each other. Statistical analysis of these metrics includes applying t-tests to find any statistically significant differences between each of these metrics in all participants' performances. Cohen's d

effect sizes for significant t-tests were also calculated for the report to evaluate the level of difference between pre- and post-surgical time points. In this regard, effect sizes between 0.2 and 0.5 are considered small, while between 0.5 and 0.8 as medium and greater than 0.8 are considered large effect sizes.

The hypothesis of the authors is that after successful surgery and rehabilitation period, participants will demonstrate a higher number of moves, more elapsed time in tasks, and a potential increase in the promptness of their moves. However, the mean angles were also compared to check for potential differences.

T-tests were performed to compare the mean of arcs of motions in performing picking up and dropping off moves in both Elevation and Plane of Elevation axes. The mean of arc of motion was compared between task 1 and task 2 in all participants.

4.3 Results

Twenty participants (Male/Female = 13/7; mean age = 69.2±7.4) consented to participate in the study prior to their SJR surgery, according to the sample size calculation. Fifteen participants returned to the lab for the 6-month period follow up test, as 5 participants refused to return for their follow up test (three participants due to choosing video clinical visits and not returning to the clinic and two participants for lack of interest). As there was no available data for their post-surgery test, the pre-surgery data was omitted from the analysis. The mean age was 67±8 years and 9/15 (60%) of the participants were male. Osteoarthritis was the primary diagnosis for 9 patients and the remainder had rotator cuff tear arthropathy. Eight participants had anatomic total shoulder arthroplasty, while the rest of the participants underwent the reverse total shoulder arthroplasty. Some of the participants of this study are mutual in the Chapter 2 and 3 studies of this dissertation.

The motion outcomes collected from all participants both prior and after 6-month rehabilitation is documented in Tables 1, 3, and 5 corresponding to Task 1, Task 2, and Task 3 of the FIT-HaNSA test. Additionally, the tables illustrate the number of completed sets. For Task-1 and Task-2, a set is counted when six motions are completed, specifically three picking and three dropping object motions. As for Task-3, a set includes three motions, for fastening and unfastening two bolts in three holes. The detailed results of tasks 1, 2, and 3 have been presented in the Appendix (A) of

the paper to avoid confusion. Detailed results include Number of Moves and sets, minimum, maximum, mean, standard deviation of AoMs along with elapsed time, promptness, workload, normalized workload and mean pickup and drop off angles for tasks 1 and 2. The results for Task-1 and Task-3 of Participant #4 were excluded from the comparison analysis because they exceeded the Z-score limit of >3, classifying them as outliers in the analysis process. However, the participant's results for Task-2 were included in the analysis.

In the task 1 results, most of the participants performed the task with a higher number of moves and time (N=11/15; 73%). On average, each participant performed 25.1 moves (SD=18.1) prior to the surgery in task 1 in comparison to 33 moves (SD=14.2) after the 6-month rehabilitation period. Average elapsed time for each participant in task 1 was 55.2 seconds (SD=32.9) prior to their surgery while it was 68 seconds (SD=25.8) after the surgery.

In the elevation axis, arc of motion range has increased in 12 out of 15 participants (80%) and average AoM in elevation was 31.1° (SD=5.6) after the 6-month post-surgery period, while it was 29.2° (SD=4.3) in pre-surgical test. The promptness increased in 13 out of 15 participants (87%) and average promptness at post-surgery test was 14.9°/s (SD=2.9) while it was 12.8°/s (SD=2.5) for pre-surgical phase of the study. Also normalized workload increased in 9 out of 15 participants (60%) with a post-surgery mean 0.31 (SD=0.2) and pre-surgery mean of 0.22 (SD=0.3).

On the other hand, the arc of motion range was reduced in 8 out 15 participants (53%) in the POE axis and average AoM in Plane of Elevation were 21.9° (SD=3) and 22.7° (SD=5.2) at post- and pre-surgery tests, respectively. The promptness increased in 9 out 15 participants (%60) and the average promptness for post-surgery and pre-surgery tests was 10.4°/s (SD=1.5) and 10°/s (SD=3.2) in POE axis, respectively. The normalized workload in POE axis increased in 10 out of 15 participants (%66) with a post-surgery mean 0.34 (SD=0.3) and pre-surgery mean of 0.26 (SD=0.3).

The t-test results along with its corresponding Cohen’s d effect size (upon its significance) and mean(SD) of all participants in task 1 is presented in Table-3. A two-tailed t-test was used to compare the Number of moves, Elapsed Time, Mean of arc of motion and promptness in both axes and the p value significance level was 0.05 (Table-3). Number of moves ($p = 0.022$) and Mean of

AoM ($p<0.001$) in elevation were statistically significantly different. The effect sizes were around medium and high, with Cohen's d of 0.48 and 0.78, respectively.

Considering the results related to task two, 10 participants performed the task with a higher number of moves (N=10/15; 66%) in post-surgery phase of the study. After the six-month rehabilitation period, each participant completed task 2 on average with 20 moves (SD=7.3), compared to 13.5 moves (SD=12.6) before the surgery. Participants #1, #7, #11 and#16 were unable to perform task two due to their inability and pain in performing the task and the required arm reach level for it. In task two, each participant's average elapsed time was 32.9 seconds (SD=28.8) before surgery and 45.2 seconds (SD=14.3) after the procedure.

The arc of motion range in the elevation plane rose in 7 out of 15 subjects (47%), and the average AoM in elevation was 41.6° (SD=4.9) in the pre-surgical test, but it increased to 45.7° (SD=5.6) following the 6-month post-surgery period. Thirteen out of fifteen patients (%87) exhibited an increase in promptness. The average promptness was 16.7°/s (SD=3.6) during the pre-surgical portion of the study and rose to 20.9°/s (SD=3.4) at post-surgery test. Normalized workload rose in 13 of 15 participants (87%), with a pre-surgery mean of 0.16 (SD=0.3) and a post-surgery mean of 0.22 (SD=0.1).

Twelve out of fifteen participants (80%) had an increase AoM in the POE axis, and the average AoM in the Plane of Elevation were 21.2° (SD=4.9) and 21.7° (SD=3.1) at the pre- and post-surgery assessments, respectively. Twelve out of fifteen (or 80%) participants' results yielded more promptness, with the average promptness for the pre-surgery and post-surgery assessments being 9.9°/s (SD=1.6) and 8.7°/s (SD=2.3) in the POE axis, respectively. Eleven out of Fifteen participants had an increase in normalized workload in the POE axis with a pre-surgery phase mean of 0.25 (SD=0.3) and post-surgery phase mean of 0.38 (SD=0.2).

Table 4 displays the t-test findings, the related Cohen's d effect size (based on its significance), and the mean (SD) for each task 2 participant. A two-tailed t-test was used on the number of moves, elapsed time, mean of the arc of motion, and promptness in both axes. The significance level was set at 5%. There was a statistically significant difference in the number of moves ($p = 0.45$), the mean of the AoM in Elevation ($p<0.01$) and promptness in Elevation ($p<0.01$). Cohen's d was 0.64

for number of moves equating to a medium effect size and 0.78, and 1.2 for the Mean of AoM and promptness of Elevation axis as high effect sizes (Table-4).

Nine of the 15 participants (60%) who performed task 3 completed a higher number of moves during the post-surgery portion of the study (Table-5). The average number of moves for participants during task 3 was 6.9 moves (SD=4.7) before surgery and climbed to 9.4 (SD=2.4) following a six-month rehabilitation period. The average elapsed time for task 3 decreased from 88.3 seconds (SD=22.4) prior to surgery to 72 seconds (SD=41.8) following the procedure.

Only 8 out of 15 participants (53%) had an increase in the arc of motion (AoM) range in the elevation plane and the average preoperative are elevation AoM of 60.5° (SD=10.3) was unchanged (60.5° SD=12) six months following treatment. Furthermore, 10 of the 15 patients (60%) had an improvement in promptness; the average promptness during the pre-surgery test was 5.6°/s (SD=1.7) and rose to 6.6°/s (SD=1.7) post-surgery test. Nine out of 15 participants (%60) showed an increase in the normalized workload of Elevation axis with a pre-surgery phase mean of 0.29 (SD=0.3) and a post-surgery phase mean of 0.39 (SD=0.2).

Nine of the fifteen subjects (60%) showed an increased range of AoM in the plane of elevation (POE) axis; the average AoM in the POE axis was found to be 105.3° (SD=8.7) at pre-surgery and 104.2° (SD=7.3) at post-surgery. Furthermore, 10 of the 15 patients (66%) showed an improvement in promptness, with the pre- and post-surgery tests recording the average promptness in all participants as 11.3°/s (SD=2.8) and 9.7°/s (SD=2.6), respectively. Normalized workload in POE axis rose in 10 of 15 subjects (66%), with a pre-surgery mean of 0.27 (SD=0.3) and a post-surgery mean of 0.34 (SD=0.2).

The p-values for the two-tailed t-test for task 3 are shown in Table-6 together with the mean (SD) and corresponding Cohen's d effect sizes (depending on significance levels). Notably, there were statistically significant variations in the number of moves ($p = 0.03$), and promptness in both Elevation ($p=0.02$) and POE axes ($p=0.02$). Regarding the effect sizes, the number of moves, and promptness in Elevation and POE axes had medium effect sizes of 0.67, 0.58 and 0.61, respectively (Table-6).

Another statistical analysis was conducted to check any statistically significant difference between the motions attributed for picking-up the jars from the lower shelf to the higher one and dropping them back to the lower one. The t-test results demonstrated that there were significant differences between pickup and drop off motions related to task 1 in Elevation axis (p=0.001) with a small to medium effect size (Cohen's d=0.44). Significant differences in both Elevation and POE in pickup/drop-off motions (p=0.002 and p=0.048) with medium and small to medium effect sizes (Cohen's d=0.53, 0.38), respectively (Table-7).

4.4 Discussion

In this study, we evaluated several motion outcomes using the Motion Shirt by comparing participants' recorded performance before and 6 months after surgery during the pre-validated FIT-HaNSA standard test. The results of the study suggest that the number of moves and motion promptness in the Elevation axis improved significantly across all three tasks. Additionally, in task 2, the mean arc of motion also showed significant statistical improvement in this cohort of participants. Moroever, this improvement was evident in terms of increased Mean AoM by 4.1°, indicating enhanced performance. The Motion Shirt demonstrated itself to be a dependable and accurate wearable sensor system capable of assessing consecutive periods of arm movement. It successfully evaluated important motion outcomes at different time periods during recovery and before SJR surgery.

Our analysis unveiled intriguing patterns in the range of motion across both Elevation and Plane of Elevation (POE) during these tasks, highlighting how the physical demands of each task require different motion patterns. However, in none of the three tasks did the elapsed time show a significant improvement. Given that the p-values for the related t-tests in all three tasks are close to the significance level, this lack of significance could be due to a statistical power issue. Increasing the sample size could potentially resolve this problem, and subsequent comparisons might then prove to be significant.

None of normalized workload t-tests were proved to be significant; however, this can be contributed to the fact that tests were conducted in a standardized context like FIT-HaNSA that movements are restricted to perform a certain series of motions. In a daily living context, a wider

range of motion is used and for a longer duration that might results in an increase workload after 6-month rehabilitation of SJR surgery [90].

Additionally, the Task 1 mean elevation Arc of Motion (AoMs) was not significantly different after treatment. This can be attributed to the fact that a narrower range of motion is required to perform this task when compared to task 2, as reported in a previous validation study. A similar point exists regarding the POE axis, as all three jars included in task 1 and task 2 are placed on a similar shelf next to each other. Therefore, participants do not require a wide range of shoulder movement for task completion.

Introducing and calculating the promptness metric allowed us to incorporate both time and mean AoM into an outcome that proved to be significantly improved in the elevation axis of all three tasks. Many participants demonstrated a higher number of moves (n=11/15 in Task 1; n=12/15 in Task 2; n=9/15 in Task 3), and increased workload and agility after the 6-month rehabilitation period following the surgery. After conducting a short dialogue, many of the participants (14 out of 15) reported feeling little to no pain compared to their pre-surgery state before performing the FIT-HaNSA test , and they were able to move their operated arms more freely and promptly. It can be estimated that after 6 months of rehabilitation, majority of participants' shoulder motion performance could improve both in terms of quantity (number of moves) and quality (promptness) of movement.

In Task 3, which involves continuous fastening and unfastening bolts, the reported angles in each participant’s performance focused on a narrower range, indicating that participants maintained a relatively fixed posture throughout the task. This stability in angles highlights the unique nature of this task compared to the others. Moreover, as there are no specified indications on the shoulder positions during this task, participants exhibited different positions of their shoulders in comparison to each other, specifically in the Plane of Elevation (POE) axis, with mean values ranging from 87.4° to 114.7°, owing to their varying arm reaches. This variability makes interpreting the obtained significant differences in promptness of both axes in this task somewhat challenging; however, it can be mentioned that overall improvements in the number of moves and elapsed time have contributed to the statistically significant improvement.

Furthermore, as shown in Table 7, it was evident that pick-up and drop-off motions differed in tasks 1 and 2, especially in the elevation plane, with a medium Cohen's d effect size. This difference could be attributed to the fact that during drop-off motions, participants benefit from gravity and use a narrower range of motion, while picking up the jars to a higher shelf requires a wider range of motion. Conversely, we did not anticipate observing differences in the Plane of Elevation (POE) axis between pick-up and drop-off motions, as no notable differences in motion occurred in this axis. However, the results demonstrated a statistically significant difference between pick-up and drop-off motions in the POE axis of task 2. One possible interpretation could again be attributed to the fact that a wider range of motion is required to perform task 2 when compared to task 1.

Another notable finding was the relatively high standard deviation values of the number of moves and elapsed time for average performances across all three tasks. This suggests that participants exhibited a wide range of performances in all three tasks, indicating that more control variables could be applied to the FIT-HaNSA test in future studies to interpret the findings to a greater extent [62]. One suggestion could be to specify a standardized position for performing the test, considering the arm reach level of the participants, and to designate precise locations for all the jars in tasks 1 and 2.

The findings of this paper were also compared with previous existing literature. Razmjou et al. [91] conducted a secondary analysis of data on 134 patients who underwent either Total Shoulder Arthroplasty (TSA) or Humeral Head Replacement (HHR). The key findings revealed significant improvements in physical symptoms, functional outcomes, range of motion, and strength for both TSA and HHR surgeries. The timing of recovery indicated that the most significant changes occurred within the first 6 months after surgery [91].

Levy et al. [12] conducted a study to assess the recovery speed and compare the effectiveness of primary anatomic TSA and reverse shoulder arthroplasty (RSA) in achieving sustained improvements in pain, function, and motion. The studied cohort included 122 patients with a minimum of 1 year of follow-up, with assessments conducted at preoperative and postoperative intervals. Results indicated significant pain relief in both patient groups, with TSA patients reaching consistent plateaus for pain and function by the 6-month mark. Notably, during this

period, TSA patients had achieved 90% to 100% of functional improvement, while RSA patients reached 72% to 91% (Levy et al., 2014).

While wearable sensor or IMU-based systems have been widely recognized for their utility in assessing shoulder motion outcomes for clinical purposes and remote rehabilitation [21,27,33,34,36,59,60,92,93]. Cooper et al. [87] conducted a study investigating the implementation of a specific wearable sensor, BPMpathway, for pre- and postoperative rehabilitation in knee replacement patients across two hospitals during the COVID-19 pandemic. Patients were equipped with the sensor during joint school before surgery and continued its use for up to 9 weeks post-surgery. The device facilitated remote monitoring of exercise progress and communication between participants and clinicians. The study reported a notable improvement in post-surgery range of motion, alongside high user compliance and positive feedback on the device's ease of use and effectiveness [87].

Overall, the study supports the Motion Shirt's effectiveness for accurately capturing motion data across standardized tasks, and utility as a tool for assessing shoulder motion metrics in the clinical settings. Furthermore, the study demonstrated an enhancement in both the quality and quantity of shoulder movements within a 6-month rehabilitation period following SJR surgeries among a cohort of patients aged 50 and above. The task-specific motion patterns observed underscore the impact of task nature on movement, offering insights for future research. With its potential to improve patient care, aid rehabilitation, prevent injuries, and contribute to musculoskeletal health research, the Motion Shirt holds promise for revolutionizing remote monitoring and providing real-time feedback in healthcare. Another significant point to consider for future researchers is the study's recruitment duration, which extended to about a year due to the challenges in recruiting participants both before and after their surgery. However, the study's limitations, such as the attrition rate (25%) due to lack of interest or choosing remote follow up after the surgery, suggest avenues for future research, including data collection in non-clinical environments such as the home and workplace and the integration of force sensors to discern differences between pre- and post-operative states.

4.5 Conclusion

The present study investigated the use of the Motion Shirt wearable sensor system in assessing motion outcomes and functional capabilities in patients undergoing SJR surgery. Participants' performances were evaluated before and 6 months after surgery via a standardized pre-validated test called the FIT-HaNSA test, focusing on shoulder joint metrics such as arc of motion (AoM) in both the Elevation and Plane of Elevation (POE) axes across three tasks of the FIT-HaNSA test.

Our findings indicated significant improvements in the number of moves and motion promptness in the Elevation axis across all three tasks post-surgery. Additionally, task-specific improvements were observed, with task 2 showing significant improvement in mean AoM in the Elevation axis. Overall, the Motion Shirt proved to be an applicable tool for assessing arm movement patterns, offering valuable insights into post-operative recovery trajectories. The Motion Shirt can be applied for monitoring post-operative recovery and guiding rehabilitation strategies in SJR patients in future applications.

4.6 List of Tables

Table 4-1. The overall results of each participant's performance in Task-1 (Post-op: After 6-month period of rehabilitation, Pre-op: Prior to the Shoulder Joint Replacement operation). [POE: Plane of Elevation]

	Elevation							POE				
	N moves	N sets	Time (s)	Promptness (°/s)	Normalized Workload (° * s)	Mean Pickup (°)	Mean Dropoff (°)	Time (s)	Promptness (°/s)	Normalized Workload (° * s)	Mean Pickup (°)	Mean Dropoff (°)
P1 - Pre-op	25	4	**56**	**11.1**	**0.14**			**56**	**10.5**	**0.21**		
P1 - Post-op	32	5	**59.2**	**13.6**	**0.19**	27.9	22.3	**59.2**	**10.7**	**0.24**	20.8	19.2
P2 - Pre-op	21	3	**37.7**	**19.4**	**0.11**			**37.7**	**19.3**	**0.17**		
P2 - Post-op	36	6	**82.1**	**20.9**	**0.56**	46.8	47.8	**82.1**	**10.8**	**0.46**	25.3	24.1
P3 - Pre-op	12	2	**27.4**	**12.2**	**0.04**			**27.4**	**8.9**	**0.04**		
P3 - Post-op	18	3	**35.3**	**15.3**	**0.08**	31.5	28.3	**35.3**	**10.6**	**0.08**	21.8	19.6
P4 - Pre-op	126	21	**281**	**13.0**	**-**			**281**	**9.8**	**-**		
P4 - Post-op	120	20	**268.4**	**13.6**	**-**	32.0	29.1	**268.4**	**9.1**	**-**	20.7	20.0

P5 - Pre-op	29	4	**72.2**	**14.5**	**0.27**			**72.2**	**11.4**	**0.37**			
P5 - Post-op	30	5	**59.6**	**17.5**	**0.25**	38.3	31.1	**59.6**	**13.4**	**0.31**	27.1	28.1
P7 - Pre-op	3	0	**8.5**	**11.6**	**0.00**			**8.5**	**5.7**	**0.00**			
P7 - Post-op	18	3	**35.7**	**14.2**	**0.07**	28.7	27.9	**35.7**	**8.9**	**0.07**	18.4	17.0
P8 - Pre-op	36	6	**79.7**	**12.3**	**0.31**			**79.7**	**9.3**	**0.37**			
P8 - Post-op	54	9	**112.5**	**12.4**	**0.62**	26.2	25.8	**112.5**	**8.6**	**0.68**	17.0	18.8
P9 - Pre-op	30	5	**70.5**	**12.6**	**0.25**			**70.5**	**13.4**	**0.42**			
P9 - Post-op	42	7	**84.3**	**15.5**	**0.44**	31.5	30.7	**84.3**	**13.2**	**0.59**	26.1	27.0
P10 - Pre-op	48	8	**99**	**13.4**	**0.52**			**99**	**10.8**	**0.67**			
P10 - Post-op	30	5	**65.2**	**13.8**	**0.23**	30.0	30.3	**65.2**	**10.1**	**0.27**	22.5	21.5
P11 - Pre-op	12	2	**30.4**	**10.3**	**0.04**			**30.4**	**8.5**	**0.05**			
	24	4	**67.7**	**9.2**	**0.17**	26.2	25.4	**67.7**	**7.9**	**0.23**	21.0	23.5

P11 - Post-op												
P12 - Pre-op	72	12	**126.2**	**15.8**	**1.00**			**126.2**	**10.1**	**1.00**		
P12 - Post-op	66	11	**120.2**	**15.5**	**0.89**	30.2	26.7	**120.2**	**10.3**	**0.93**	19.3	18.8
P13 - Pre-op	15	2	**36.7**	**13.9**	**0.07**			**36.7**	**7.0**	**0.06**		
P13 - Post-op	42	7	**72.8**	**19.7**	**0.41**	36.9	31.4	**72.8**	**11.3**	**0.38**	19.0	20.3
P14 - Pre-op	24	8	**60.8**	**9.4**	**0.14**			**60.8**	**7.7**	**0.18**		
P14 - Post-op	21	3	**45.3**	**14.3**	**0.12**	31.7	29.4	**45.3**	**11.0**	**0.14**	23.0	24.7
P16 - Pre-op	6	1	**13.3**	**9.7**	**0.01**			**13.3**	**10.5**	**0.01**		
P16 - Post-op	18	3	**41.8**	**12.4**	**0.09**	30.0	27.2	**41.8**	**10.5**	**0.12**	23.8	25.1
P17 - Pre-op	18	3	**54.8**	**11.9**	**0.14**			**54.8**	**7.6**	**0.14**		
P17 - Post-op	30	5	**70.4**	**15.2**	**0.30**	37.0	34.5	**70.4**	**9.7**	**0.30**	21.1	24.5

Table 4-2. The mean(SD) and t-test results of all participants performances in Task-1 for number of moves, Time, Mean of AOE and Promptness in Elevation and Plane of Elevation axes (* sign represents p-value<0.05).

TASK-1					
	Mean (SD)				
	Pre-Surgery	Post-Surgery	Difference	t-test (p-value)	Effect size
NUMBER OF MOVES	25.1(18.1)	33 (14.2)	7.9	0.022*	**0.48**
ELAPSED TIME (S)	55.2(32.9)	68(25.8)	12.8	0.06	0.43
MEAN AOM_ELEVATION (°)	29.2(4.3)	31.1(5.6)	1.9	0.1	0.39
MEAN AOM_POE (°)	22.7(5.2)	21.9(3)	-0.8	0.39	0.18
PROMPTNESS_ELEVATION (°/S)	12.8(2.5)	14.9(2.9)	2.1	<0.001*	**0.78**
PROMPTNESS_POE (°/S)	10(3.2)	10.4(1.5)	0.4	0.61	0.15
NORM_WORKLOAD_ELEVATION (° * S)	0.22(0.3)	0.31(0.2)	0.09	0.08	0.38
NORM_WORKLOAD_POE (° * S)	0.26(0.3)	0.34(0.3)	0.08	0.14	0.3

Table 4-3. The results of each participant's performance in Task-2 (Post-op: After 6-month period of rehabilitation, Pre-op: Prior to the Shoulder Joint Replacement operation). [POE: Plane of Elevation]

	Elevation							POE				
	N moves	N sets	Time (s)	Promptness (°/s)	Normalized Workload (° * s)	Mean Pickup (°)	Mean Dropoff (°)	Time (s)	Promptness (°/s)	Normalized Workload (° * s)	Mean Pickup (°)	Mean Dropoff (°)
P1 - Pre-op												
P1 - Post-op	18	3	**36.3**	**17.0**	**0.11**	37.0	31.4	**36.3**	**13.9**	**0.23**	19.0	20.4
P2 - Pre-op	12	2	**33.6**	**16.3**	**0.08**			**33.6**	**8.2**	**0.16**		
P2 - Post-op	18	3	**45.8**	**22.2**	**0.24**	56.4	56.4	**45.8**	**9.7**	**0.36**	23.9	25.5
P3 - Pre-op	6	1	**15.2**	**16.0**	**0.00**			**15.2**	**10.7**	**0.04**		
P3 - Post-op	12	2	**28.6**	**19.4**	**0.07**	47.5	44.9	**28.6**	**11.3**	**0.16**	27.5	26.4
P4 - Pre-op	27	4	**60.2**	**19.1**	**0.37**			**60.2**	**11.9**	**0.76**		
P4 - Post-op	30	5	**58.7**	**21.7**	**0.40**	43.7	41.1	**58.7**	**9.4**	**0.57**	19.7	16.9

P5 - Pre-op	8	1	**25.6**	**14.5**	**0.03**			**25.6**	**6.2**	**0.07**			
P5 - Post-op	12	2	**23.8**	**24.9**	**0.06**	55.9	42.9	**23.8**	**11.3**	**0.11**	22.9	22.1	
P7 - Pre-op													
P7 - Post-op	12	2	**25.7**	**18.0**	**0.05**	37.7	39.4	**25.7**	**8.7**	**0.10**	17.8	19.5	
P8 - Pre-op	18	3	**38.5**	**18.3**	**0.13**			**38.5**	**9.8**	**0.26**			
P8 - Post-op	33	5	**63.8**	**20.0**	**0.44**	40.2	36.7	**63.8**	**9.6**	**0.69**	18.2	18.8	
P9 - Pre-op	18	3	**43.8**	**18.7**	**0.18**			**43.8**	**11.6**	**0.40**			
P9 - Post-op	30	5	**65.4**	**20.9**	**0.48**	48.0	43.1	**65.4**	**12.0**	**0.91**	26.2	26.0	
P10 - Pre-op	24	4	**48.8**	**24.9**	**0.31**			**48.8**	**10.6**	**0.44**			
P10 - Post-op	18	3	**40.4**	**24.1**	**0.20**	54.3	53.7	**40.4**	**8.5**	**0.24**	18.8	19.2	
P11 - Pre-op	18	3	**65.6**	**11.0**	**0.25**	41.7	38.1	**65.6**	**7.5**	**0.57**	25.4	29.2	

P11 - Post-op													
P12 - Pre-op	45	7	**102.2**	**17.3**	**1.00**			**102.2**	**6.9**	**1.00**			
P12 - Post-op	21	3	**52.0**	**15.9**	**0.22**	39.8	38.7	**52.0**	**7.9**	**0.38**	19.8	19.3	
P13 - Pre-op	8	2	**20.1**	**14.5**	**0.01**			**20.1**	**6.7**	**0.05**			
P13 - Post-op	30	5	**49.1**	**26.3**	**0.34**	45.4	40.5	**49.1**	**12.4**	**0.53**	18.8	21.8	
P14 - Pre-op	18	3	**48.9**	**13.0**	**0.15**			**48.9**	**6.0**	**0.25**			
P14 - Post-op	18	3	**43.1**	**18.5**	**0.17**	44.2	44.2	**43.1**	**8.4**	**0.28**	17.9	22.2	
P16 - Pre-op													
P16 - Post-op	12	2	**30.5**	**18.0**	**0.07**	47.9	43.3	**30.5**	**10.6**	**0.18**	25.9	28.1	
P17 - Pre-op	18	3	**55.5**	**11.9**	**0.19**			**55.5**	**6.8**	**0.37**			
P17 - Post-op	18	3	**48.5**	**16.2**	**0.19**	45.3	41.7	**48.5**	**8.7**	**0.36**	19.7	26.9	

Table 4-4. The mean(SD) and t-test results of all participants performances in Task-2 for number of moves, Time, Mean of AOE and Promptness in Elevation and Plane of Elevation axes (* sign represents p-value<0.05).

TASK-2					
	Mean (SD)				
	Pre-surgery	Post-surgery	Difference	t-test (p-value)	Effect size
NUMBER OF MOVES	13.5(12.6)	20(7.3)	6.5	0.045*	**0.64**
ELAPSED TIME (S)	32.9(28.8)	45.2(14.3)	12.3	0.09	0.54
MEAN AOM_ELEVATION (°)	41.6(4.9)	45.7(5.6)	4.1	0.007*	**0.78**
MEAN AOM_POE (°)	21.2(4.9)	21.7(3.1)	0.5	0.69	0.04
PROMPTNESS_ELEVATION (°/S)	16.7(3.6)	20.9(3.4)	4.2	0.008*	**1.2**
PROMPTNESS_POE (°/S)	8.7(2.3)	9.9(1.6)	1.2	0.14	0.2
NORM_WORKLOAD_ELEVATION (° * S)	0.22 (0.1)	0.16(0.3)	-0.06	0.43	0.26
NORM_WORKLOAD_POE (° * S)	0.38(0.2)	0.25(0.3)	-0.13	0.15	0.45

Table 4-5. The overall results of each participant's performance in Task-3 (Post-op: After 6-month period of rehabilitation, Pre-op: Prior to the Shoulder Joint Replacement operation). [POE: Plane of Elevation]

	Elevation					POE		
	N moves	N sets	Time (s)	Promptness (°/s)	Normalized Workload (° * s)	Time (s)	Promptness (°/s)	Normalized Workload (° * s)
P1 - Pre-op	5	1	**54.6**	**4.8**	**0.1**	**54.6**	**8.7**	**0.09**
P1 - Post-op	10	3	**68.1**	**7.1**	**0.25**	**68.1**	**12.8**	**0.22**
P2 - Pre-op	2	0	**24.3**	**4.1**	**0.00**	**24.3**	**8.6**	**0.00**
P2 - Post-op	9	3	**92.7**	**5.9**	**0.395**	**92.7**	**9.4**	**0.37**
P3 - Pre-op	10	3	**105.9**	**5.0**	**0.44**	**105.9**	**9.9**	**0.43**
P3 - Post-op	9	3	**110.2**	**4.5**	**0.43**	**110.2**	**9.0**	**0.42**
P4 - Pre-op	36	12	**300.0**	**5.9**	-	**300.0**	**12.6**	-
P4 - Post-op	12	4	**92.9**	**9.9**	-	**92.9**	**13.0**	-

P5 - Pre-op	2	0	**25.1**	**4.5**	**0.00**	**25.1**	**7.5**	**0.00**
P5 - Post-op	6	3	**69.4**	**4.8**	**0.17**	**69.4**	**8.8**	**0.15**
P7 - Pre-op	2	0	**36.2**	**3.8**	**0.02**	**36.2**	**5.4**	**0.01**
P7 - Post-op	7	2	**75.4**	**6.3**	**0.27**	**75.4**	**9.2**	**0.19**
P8 - Pre-op	3	1	**63.4**	**4.0**	**0.11**	**63.4**	**4.4**	**0.07**
P8 - Post-op	8	2	**82.4**	**6.7**	**0.35**	**82.4**	**9.4**	**0.24**
P9 - Pre-op	12	4	**152.5**	**4.2**	**0.79**	**152.5**	**9.3**	**0.85**
P9 - Post-op	12	4	**142.6**	**4.2**	**0.69**	**142.6**	**9.0**	**0.72**
P10 - Pre-op	9	3	**116.7**	**3.8**	**0.41**	**116.7**	**9.0**	**0.47**
P10 - Post-op	6	2	**62.1**	**5.5**	**0.15**	**62.1**	**10.8**	**0.15**
P11 - Pre-op	6	2	**52.4**	**6.4**	**0.13**	**52.4**	**11.2**	**0.10**
P11 - Post-op	9	3	**90.7**	**5.6**	**0.36**	**90.7**	**10.0**	**0.31**

P12 - Pre-op	18	6	**130.1**	**7.4**	**1.00**	**130.1**	**12.5**	**1.00**
P12 - Post-op	15	5	**97.1**	**8.1**	**0.61**	**97.1**	**16.4**	**0.60**
P13 - Pre-op	3	1	**27.8**	**8.0**	**0.03**	**27.8**	**11.4**	**0.02**
P13 - Post-op	12	4	**69.5**	**9.1**	**0.34**	**69.5**	**16.8**	**0.31**
P14 - Pre-op	10	3	**70.3**	**8.8**	**0.34**	**70.3**	**13.7**	**0.25**
P14 - Post-op	9	3	**67.8**	**8.1**	**0.28**	**67.8**	**15.0**	**0.26**
P16 - Pre-op	5	2	**49.9**	**6.0**	**0.10**	**49.9**	**11.4**	**0.1**
P16 - Post-op	9	3	**97.2**	**5.6**	**0.42**	**97.2**	**9.9**	**0.36**
P17 - Pre-op	9	3	**99.2**	**7.6**	**0.59**	**99.2**	**9.6**	**0.36**
P17 - Post-op	10	3	**110.7**	**7.7**	**0.75**	**110.7**	**9.8**	**0.47**

Table 4-6. The mean(SD) and t-test results of all participants performances in Task-3 for number of moves (fastening/unfastening), Time, Mean of shoulder angle and Promptness in Elevation and Plane of Elevation axes (* sign represents p-value<0.05).

TASK-3					
	Mean (SD)				
	Pre-surgery	Post-surgery	Difference	t-test (p-value)	Effect size
NUMBER OF MOVES	6.9(4.7)	9.4(2.4)	2.5	0.03*	**0.67**
ELAPSED TIME (S)	72(41.8)	88.3(22.4)	16.3	0.09	0.48
MEAN ANGLE_ELEVATION (°)	60.5(12)	60.5(10.3)	0	0.99	0.0
MEAN ANGLE_POE (°)	105.3(8.7)	104.2(7.3)	-1.1	0.6	0.1
PROMPTNESS_ELEVATION (°/S)	5.6(1.7)	6.6(1.7)	1	0.02*	**0.58**
PROMPTNESS_POE (°/S)	9.7(2.6)	11.3(2.8)	1.6	0.02*	**0.61**
NORM_WORKLOAD_ELEVATION (° * S)	0.39(0.2)	0.29(0.3)	-0.1	0.13	0.39
NORM_WORKLOAD_POE (° * S)	0.34(0.2)	0.27(0.3)	-0.07	0.25	0.28

Table 4-7. The mean(SD) and t-test results of all participants performances in task 1 and task 2 for pickup and drop-off motions in Elevation and Plane of Elevation axes (* sign represents p-value<0.05).

KUP/DROP OFF MOVEMENT (POST-SURGERY)				
	(SD)			
	p	off		t size
KUP/DROP OFF ELEV- TASK 1 (°)	6.4)	5.8)	*	
KUP/DROP OFF POE- TASK 1 (°)	2.9)	3.4)		
KUP/DROP OFF ELEV- TASK 2 (°)	6.4)	5.7)	*	
KUP/DROP OFF POE- TASK 2 (°)	3.6)	3.6)	*	

4.7 List of Figures

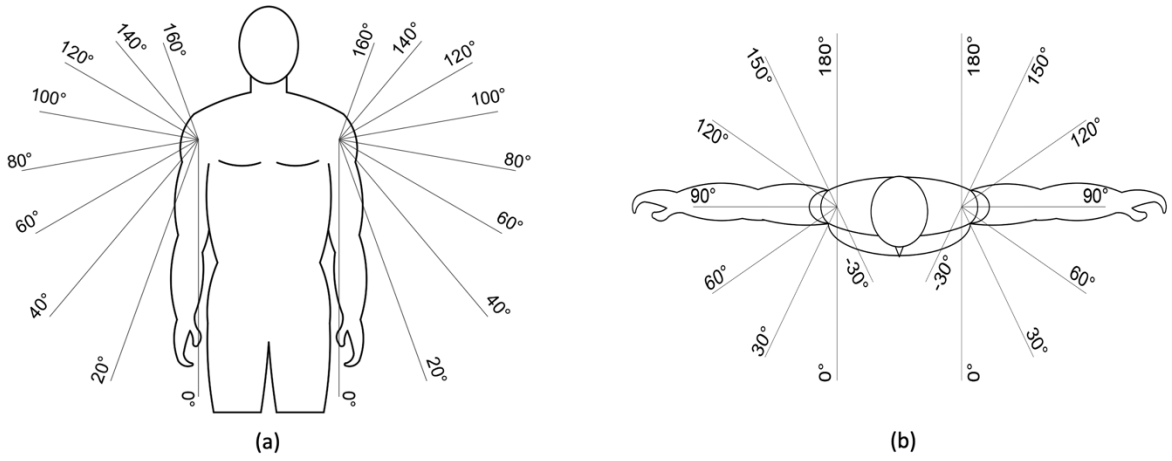

Figure 4-1. Specification and range of "Elevation" (a) and "Plane of Elevation" (b) as per Langohr et al.

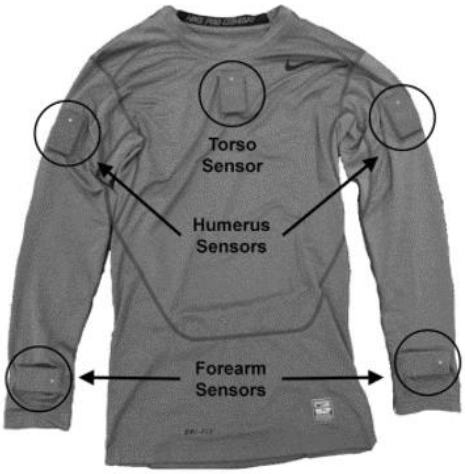

Figure 4-2. "Motion Shirt", as the developed wearable sensor system of the study; including 5 IMU sensors placed into sewn pockets on the specified locations.

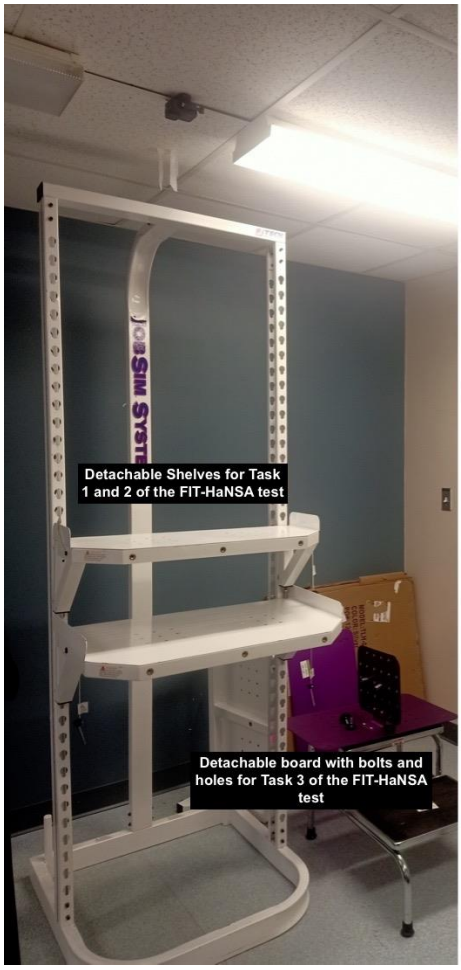

Figure 4-3. Configured setup for the FIT-HaNSA test using the Job-Sim settings.

Chapter 5

5 Reliability and validity of using smartphone sensor and photography to measure hand and upper extremity joints range of motion; A systematic review

This study has been submitted to Biomedical Physics & Engineering Express Journal.

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Abstract

Aim/Background: The aim of this systematic review was to appraise and synthesis the available evidence on the reliability and validity of smartphone sensors and photography in assessing the ROM of hand and upper extremity joints.

Method: We searched the literature from the beginning to January 2023 to find relevant studies. We included studies in which "smartphone sensor" or "smartphone photography" was employed as the method of upper limb ROM measurement and compared these methods to conventional goniometer as the gold standard and validated ROM measurement techniques. Two independent reviewers (SM and ES) assessed the methodological quality of reliability and validity of both category of studies using the Quality Appraisal Tool for studies of diagnostic Reliability (QAREL) and the Quality Assessment of Diagnostic Accuracy Studies (QUADAS-2) tools, respectively. Qualitative synthesis was the preferred method of summarizing and presenting the results.

Results: A total of 31 studies were included in this study. The sample size across studies ranged from 10 to 171, and the mean age was 41 years old. Almost all the studies included in the photography category, except for one, stated the good to excellent reliability or validity of this method in comparison to the goniometric measurements. Eight studies in the smartphone sensor category reported excellent reliability or validity (%47), seven studies stated good level of reliability or validity (%41), and two studies reported average or moderate level of reliability (12%). The quality assessment using the QAREL assessment tool was high in 11 studies (35%), moderate in 8 studies (26%) or low in 12 studies (39%). In the smartphone photography category, eight studies relied solely on the smartphone cameras to capture images, which were subsequently

analyzed using computer software. While four studies used DrGoniometer application, and two studies used mROM and RateFast Goniometer applications where the entire image capture and analysis process was carried out through smartphone application software. In the smartphone sensor category, the use of smartphone applications for measuring arcs of motion varied, featuring notable applications like Goniometer pro, Gyroscope, and Clinometer. The predominant method involved securing smartphones with an elastic band, and the majority of studies applied blinding to assessors.

Conclusion: The results of this review provide clinicians and researchers with evidence to support using smartphone photography and sensor applications for the purpose of hand and upper extremity ROM assessment. Measuring ROM using smartphone is a valid and reliable method and can be used for telerehabilitation purposes instead of the hand-held goniometer.

Lay Summary: Using smartphone-based measurements facilitates telerehabilitation and increases patient adherence to treatment and compliance.

Key words: Telerehabilitation; Range of motion measurement; Smartphone; Technology

5.1 Introduction

Range of motion (ROM) measurement is an essential part of clinical assessment and decision-making for clinicians to keep track of patients' improvements. Hand-held goniometry (universal goniometer; UG) is one of the most common, reliable, and valid method for measuring ROM [94]. In other words, it is the gold standard for clinical ROM measurement [94]. Also, visual ROM estimation is sometimes used in routine clinical practices by experts [95]. However, there are some factors that can compromise the accuracy and reliability of the manual goniometry or introduce challenges in measurements, such as displacement of the goniometer axis or the time required performing manual goniometry [96].

The use of smartphones by healthcare providers for medical purposes is increasing due to the growing number of downloadable health, fitness, and medical apps available in both assessments and treatments. A tendency of transition from manual to digital medical assessment seems to be

occurring as a result of the fast-evolving pace of technology development in healthcare [97,98]. However, it is important to investigate the reliability and validity of the these new applications.

Advances in smartphone technologies, including high-resolution cameras, 3D scanners, magnetometers, accelerometers, gyroscopes, or mobile-based applications, have resulted an increase in the use of smartphones and digital devices in routine patient care [99,100]. These platforms can potentially facilitate health care delivery for both patients and health care providers and improve adherence to treatment. Most recently (since 2020), the COVID-19 pandemic has accelerated interest in telerehabilitation services to increase patient access and adherence to treatment [101].

In recent years, the number of studies evaluating the reliability, validity, and accuracy of smartphone sensors and photography for ROM assessment has increased. Given that the use of smartphone technologies in the delivery of healthcare services is an emerging practice, it is important for clinicians and researchers to evaluate and report the measurement properties of smartphone sensor and photography for ROM assessment to be confident in the results generated by this method.

The aim of this systematic review was to appraise and synthesize the literature on the reliability and validity of both smartphone sensors and smartphone photography in the hand and upper extremity ROM measurement compared with valid and reliable tools of ROM measurement.

5.2 Methods

We searched the literature from the first studies found in databases since January 2000 to January 2023 to find relevant studies using MEDLINE, EMBASE, Scopus, and Google Scholar databases. Further, reference lists of the previous reviews and relevant papers were searched. The search keywords and Boolean operators for smartphone sensors (AND or OR) were:

(mobile phone OR smart phone OR cell phone OR digital) AND (IMU OR inertial measurement unit OR Accelerometer OR Gyroscope OR inertial sensor) AND (range of motion OR

measurement) AND (hand OR upper limb OR upper extremity OR wrist OR forearm OR elbow OR shoulder OR finger) AND (reliability OR validity OR accuracy)

For the smartphone photography the keywords and operators:

(mobile phone OR smart phone OR cell phone OR digital) AND (photography OR application OR app OR software) AND (range of motion OR measurement) AND (hand OR upper limb OR upper extremity OR wrist OR forearm OR elbow OR shoulder OR finger) AND (reliability OR validity OR accuracy).

We set no limitations in terms of the date and language of publications. We used the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) criteria to identify, select, and critically appraise relevant research studies in this field [102] (Figure 5-1, Figure 5-2).

5.2.1 Inclusion and Exclusion Criteria

We included studies using sensor embedded with smartphones or photographs collected with a smartphone as a means of assessing upper limb joint motion and that addressed at least one psychometric property of reliability or validity. The studies were published in peer-reviewed journals and in full-text original papers. Reviews, poster presentations, letters to the editor, commentaries, and theses were excluded. Also, we excluded studies that did not use universal (or manual) goniometer as the reference for measurement comparisons. Additional exclusion criteria included studies that measured non-standardized movements, such as daily life activities, or those in which no assessment and evaluation of range of motion were conducted.

5.2.2 Study Selection

Two independent reviewers (SM and ES) carried out two different database searches (photography and sensor) separately. The same reviewers conducted deduplication. In the next step, each reviewer performed title and abstract checking and marked the potentially eligible studies for both categories for the last stage. Finally, the reviewers conducted full-text reviews and identified the eligible studies for inclusion in each category of smartphone sensor and photography applications.

Where there was any disagreement between the two reviewers in any stage of study search, consensus was reached by discussing the details with a clinical research specialist.

5.2.3 Data Extraction

One reviewer (SM) investigated each study to extract the following data from the included studies: author name, year of publication, country of publication, sample size, mean age, or age range, methods of ROM measurement, plane of photography (or smartphone placement location), and the results of reliability, validity, or accuracy of the ROM measurement methods. All extracted data were double checked by the second author (ES).

5.2.4 Quality appraisal and risk of bias assessment tool

Two independent reviewers (ES and SM) assessed the methodological quality of reliability and validity studies using the Quality Appraisal Tool for studies of diagnostic Reliability [103] (QAREL) and the Quality Assessment of Diagnostic Accuracy Studies [104] (QUADAS-2), respectively. The QAREL is an 11-item quality appraisal tool for diagnostic reliability studies that measures sampling bias, representativeness of participants and raters, rater's blinding, order of examination, time interval between repeated measures, application and interpretation of tests, and appropriateness of statistical analysis. Each item is rated as "yes", "no", "unclear", or "not applicable". Based on previous systematic reviews [105], the overall quality of the reliability studies was reported based on the ratio of "yes" to other responses and rated as high (67% or more), moderate (50%–66%), and low (<50%).

The QUADAS is a list of 14 questions, each of which is rated as "yes", "no", or "unclear", covering the domains of Representative sample, Selection criteria, Appropriate reference standard, Stability of target condition, Appropriate sample received reference standard, Same reference standard to all, Reference standard independent of the index, Index test detailed, Reference standard detailed, Independent interpretation of index test, Independent interpretation of reference standard, Clinical data available similar to that in practice, Uninterruptable/intermediate test results reported, and Withdrawals explained. Based on the guidelines [105], a high-quality study is one with a total score of >60% (ratio of "yes" to "other" responses).

Any disagreement on the rating of the items in the critical appraisal tools was resolved through consensus between the reviewers. The weighted Kappa was used to demonstrate the level of agreement between the two raters.

5.2.5 Synthesis of Results

We performed quality appraisals and summarized the literature on the reliability, validity, and accuracy of the mobile phone sensors and photography applications used for upper limb ROM measurements. The results were categorized and presented for the upper limb region. The summary of the main results of the studies was provided as two separate tables along with the results of methodological quality assessments.

Role of the Funding Source:

The funder played no role in the design, conduct, or reporting of this study.

5.3 Results

5.3.1 Smartphone Photography Applications:

Our literature search identified 1024 studies through databases (EMBASE: 313; Medline: 404; Scopus: 205, Google Scholar: 242). After deduplication and title abstract checking, 92 studies were left for full-text checking. A total of 14 studies were eligible to be included in this study [22,24,25,106–116]. The sample size across studies ranged from 28 to 94, and the mean age was 44 years old. Various hand and upper extremity conditions were included in the primary studies, including distal radius fractures [22,24], Dupuytren fixed flexion contracture [106], shoulder pathologies [25], elbow contractures [112], and flexor tendon repairs [114]. Also, ten studies included healthy participants for the ROM measurement [24,25,107–111,113,115,116].

The method of digital photography varied across the studies. Eight studies [22,106–109,112,114,115] used the camera of the smartphones directly to take the picture, and then analyzed it by a computer software for measuring ROM. However, three studies [24,110,111] used DrGoniometer and two other studies used mROM [25] and RateFast [113] Goniometer applications to take a desired picture through

the application and then analyze the picture in the application for the ROM measurement. For finger and wrist ROM, the transverse plane was used for photography. Measurements of shoulder abduction and forearm pronation/supination were all taken in the frontal plane. The sagittal plane was used to evaluate the ROM of both the elbow and the shoulder flexion-extension and shoulder external rotation (Table 5-1).

Quality assessment of reliability and validity studies:

The results of the reliability (QAREL) and validity (QUADAS) methodological quality assessment are presented in Tables 5-2 and 5-3. High agreement was obtained between the reviewers for methodological quality assessment (Kappa: 0.89)

The results of the QAREL assessment indicated that six studies [24,25,106,108,110,115] (6/14; 43%) were rated as high quality, four studies [22,107,109,112] (4/14; 29%) as moderate quality, and four studies [111,113,114,116] (4/14; 29%) as low quality. Two items of the QAREL (blinded to clinical information and additional cues) were rated as not applicable for all studies since recognition of clinical information and cues could not compromise the reliability of the ROM measurement and bias the results of the study. Four items were rated as "yes" for nearly all studies, including representative sample, representative raters, correct application of the test, and taking appropriate statistical tests.

The results of the QUADAS assessment indicated that all studies were of high quality in terms of validity. Although not all items were rated as "yes", the overall quality of all studies was high. There were some pitfalls in the reports of the validity of smartphone photography for ROM measurement in some studies, including recruiting only healthy participants, not reporting the details of the ROM measurement method, not explaining the withdrawals, or reporting uninterpretable test results.

Wrist ROM:

Three studies [22,24,107] assessed the reliability and validity of direct smartphone photography in the measurement of wrist ROM. M. Ge et al. [22], captured two series of photographs, surgeon's and patient's photography, of 38 patients with DRFs. The ROM was measured using analytic software

in computer. In the other study, Wagner et al. [107] recruited 32 healthy participants (64 wrists). The authors analyzed the captured photographs by Adobe Photoshop to measure the ROM. The results of both studies indicated that direct smartphone photography is a reliable and valid method for measuring wrist ROM. Furthermore, no significant difference was found between the pictures of patients and surgeons.

In another study by Reid et al. [24] the reliability and validity of smartphone photography, using DrGoniometer application, was evaluated in 30 patients with DRF and healthy participants. The authors found that DrGoniometer demonstrated high reliability and validity in participants with DRF, but not healthy subjects. In healthy subjects, both methods (DrGoniometer and UG) demonstrated poor inter-rater reliability.

Elbow ROM:

Five studies [108,109,111,112,116] evaluated the reliability and validity of smartphone photography in the measurement of elbow ROM in a total of 180 patients with elbow contractures and healthy participants.

In a study by Keijsers et al. [108], elbow ROM measurement with digital photography was compared with video measurement, smartphone application, and UG in 40 healthy participants. Based on the results of this study, smartphone photography could be considered as a reliable and valid method of elbow ROM measurement compared to the other alternative methods.

In another study, Meislin et al. [109] compared photographs taken by subjects with the photographs taken by surgeons and UG, in 32 healthy individuals (64 elbows). The results of this study indicated that using smartphone photography for the purpose of elbow ROM measurement by patients could be considered as a reliable and valid method compared to surgeon's photography and UG.

Ferriero et al. [111] evaluated the reliability of DrGoniometer application in 28 healthy individuals and they concluded that DrGoniometer application is a reliable method of measuring elbow ROM

and can be considered as an alternative or additional method to the conventional methods of the elbow ROM measurement.

Reliability of self-taken photographs (selfies) as a method of measuring ROM was also evaluated in a study by Shields et al. [112] in 50 subjects with elbow contractures. They concluded that selfies of elbow flexion–extension could be considered a reliable and accurate tool for measuring elbow range of motion. The authors also concluded that measurement errors of selfies are also negligible and do not have significant impact on the ROM measurement.

Lam et al., also assessed both shoulder and elbow motions using analytic software on iPad pro [116] via a processing system called marker less motion capture (MMC). However, they reported that the iPad MMC system generally underestimated the shoulder and elbow Active ROM. This inconsistency indicates that the assessed system might not currently be a reliable replacement for goniometry in clinical use [116].

Shoulder ROM:

Three studies [25,110,113] evaluated reliability and validity of shoulder ROM measurement with three different smartphone applications, mROM, DrGoniometry, RateFast Goniometer, in 184 healthy participants and patients with shoulder pathologies. mROM application was compared with inertial sensors in 37 healthy participants and patients with shoulder pathology [25]; DrGoniometry was compared with UG and GetMyROM application (inclinometery-based) in 94 healthy participants [110]; RateFast Goniometer was compared with UG and Protractor (to test the accuracy in the measurement of a predefined angle) in 53 healthy participants [113].

The results of the three studies indicated that digital photography using smartphone applications could be considered as a reliable and valid method for the purpose of shoulder ROM measurement.

Hand ROM:

Three studies evaluated reliability and validity of smartphone photography for the hand ROM measurement in a total of 159 patients with Dupuytren fixed flexion contracture, flexor tendon

repairs and healthy participants. John Z. Zhao et al. [106] evaluated the reliability of two series of photographs, trained photos by research staff, untrained photos by patient's family members for the measurement of the Dupuytren fixed flexion contracture. In another study, Chen et al. [114] evaluated the reliability of smartphone photography in 37 fingers after flexor tendon repair of the hand. Gu et al., developed an image-processing system that obtains the finger joint angles using an open-source software called MediaPipe [115]. Their results indicated a strong correlation and an excellent level of reliability in majority of finger joint measurements through comparison with the gold-standard [115]

All three studies indicated that finger ROM measurements using smartphone photography, if taken properly, could be considered as reliable as conventional goniometry measurements.

5.3.2 Smartphone Sensor Applications

Our comprehensive literature search encompassed 675 studies from various databases (Scopus: 71, EMBASE: 99, Medline: 84, Google Scholar: 421). Following deduplication and title-abstract scrutiny, 47 studies were subjected to full-text examination. Ultimately, 17 studies met the eligibility criteria for inclusion in this study [117–133] (Table 5-4).

The sample sizes across the selected studies ranged from 10 to 171 participants, with a mean age of 39 years. A diverse array of hand and upper extremity conditions were investigated in the primary studies, including Olecranon fracture repair [125], Dupuytren's disease [131], distal extremity fracture and ligament injury [124], shoulder pathologies [126,127], wrist impingement syndrome [129], and hand injury [133]. Additionally, twelve studies included healthy participants for range of motion (ROM) measurements [117–124,126,128,130,132].

The smartphone applications employed for measuring arcs of motion or ROM varied due to the continuous development of smartphones over the past decade. Noteworthy applications included Goniometer pro (currently unavailable on official application stores) [117,120], the Gyroscope application (Acrossair Co, San Francisco, CA; currently unavailable on official application stores) [118,123,124], and the Clinometer (Plaincode Software Solutions, Stephanskirchen, Germany) [122,125,126,129]. The predominant method involved securing smartphones on the area of interest using

an elastic band for measurements. Moreover, the majority of the studies (11/17;65%) applied at least one form of blinding to assessors to prevent the bias potential impact on their outcomes. Twelve of the reviewed papers (71%) recruited professional or expert assessors to perform the measurements indicating that most researchers performed the measurements in a standardized setting.

Among the seventeen reviewed studies, Six concentrated on shoulder ROM measurements [126–130,132], four focused on elbow and forearm measurements [121,122,124,125], five evaluated wrist measurements [117–120,123], and two assessed finger joint ROM [131,133] (Table 5-4).

Quality assessment of reliability and validity studies:

The results of the methodological quality assessments for reliability (QAREL) and validity (QUADAS) are delineated in Tables 5-5 and 5-6, respectively. Remarkably, a high level of consensus emerged among the reviewers during the evaluation of methodological quality, as reflected by a Kappa coefficient of 0.91.

Upon QAREL assessment, it was discerned that out of the total 17 studies, five (29%) [117,122,124,126,130] were classified as high quality, four (24%) [120,121,127,129] as moderate quality, and eight (47%) were deemed low quality. Similar to the photography section, two components of the QAREL—namely, blinding to clinical information and additional cues—were deemed not applicable across all studies due to similar circumstances. Noteworthy exceptions were observed for two items: "correct application of the test" and "taking appropriate statistical tests," both of which received a "yes" for almost all studies. The only deviations were noted in two studies [123,132], where detailed statistical results were not provided.

Turning to the QUADAS assessment, it was found that all 14 studies in this assessment demonstrated high quality in terms of validity. While not every individual item received a "Y" rating, the aggregate quality of the studies remained consistently high. Some aspects of the QUADAS assessment were not properly addressed in the papers pertaining to the validity of smartphone sensors for Range of Motion (ROM) measurement. These shortcomings included the exclusive recruitment of healthy participants, absence of detailed explanations regarding the ROM

measurement method, failure to explain withdrawals, neglecting independent interpretation of reference or index results, and reporting of test results that were considered uninterpretable.

Wrist ROM:

Two studies [117,120] assessed the reliability and validity of a smartphone application called Goniometer pro in the measurement of wrist ROM recruiting 40 and 73 healthy participants. Both studies placed the phone on the dorsal side of the wrist and performed the measurements. Both studies reported excellent inter-rater reliability (ICC>=0.79) and excellent level of agreement in validity (r>=0.8).

In two other studies [118,123], the Gyroscope application was utilized for the purpose of wrist ROM measurements. Similarly healthy participants were recruited with relatively sufficient sample sizes of 171 and 52, respectively. Similarly, the researchers attached the smartphone to the dorsal side of the hand; however, merely the difference values of goniometer and application measurements along with results of t-tests were reported and analyzed. Lendner et al., also interpreted and demonstrated a Bland-Altman plot to compare the measurements and the results did not demonstrate any bias inherent all wrist movement measurements [118]. Both studies reported good to excellent level of agreement and no statistical difference between the universal goniometric measurements and the application.

Another study by Engstrand et al., placed the smartphone in the palm of the hand to perform the wrist measurements on 33 healthy participants [119]. The utilized application was the WristCheck (a self-developed mobile application). They reported excellent inter-rater reliability levels (>=0.83) for all wrist movements except for pronation (ICC=0.59). Finally, they concluded that smartphone sensors are accurate and demonstrate excellent test-retest reproducibility and are worthy candidates to replace traditional goniometric measurements [119].

Elbow ROM:

Four studies [121,122,124,125] evaluated the reliability and validity of smartphone sensors in the measurement of elbow ROM in a total of 212 patients with elbow injuries and healthy participants.

Two studies used commercial (currently outdated) Bubble inclinometer-based and the gyroscope applications to measure the elbow ROM measurements [121,124]. Behnoush et al., focused on 60 healthy participants and reported excellent inter-rater reliability (ICC>0.9) and high level of validity (>=0.73) in all forearm moves using a smartphone application [121]. Additionally, Santos et al. focused on both 20 healthy participants and 20 injured patients. They concluded the smartphone measurements demonstrate an excellent inter-observer reliability for smartphone-based methods with an agreement of plus or minus 2° [124].

In two other studies [122,125], the Clinometer application is used, and the phone mimed a universal goniometer measurement. Pottorf et al. compared the measurements on healthy participants and reported strong correlations between application and goniometer measurements and thus validity of smartphone application. They provide evidence to support the reliability and validity of a smartphone when assessing joint ROM of forearm supination and pronation [122]. Moreover, Vauclair et al., focused on patients with a unilateral healed olecranon fracture and assessed the flexion/extension and pronation/supination moves of forearms. They only reported mean difference values and t-test results and they concluded that the application tends to overstate flexion in comparison to the goniometer, and it is advisable to exercise caution when utilizing it to assess patient progress in relation to prior measurements [125].

Shoulder ROM:

Six studies [126–130,132] evaluated reliability and validity of shoulder ROM measurement with different smartphone applications including the Clinometer, GetMyROM, Peerwell, Goniometer Records, and SDK in 205 healthy participants and patients with shoulder pathologies. The Clinometer was used in two studies [126,129], which both included 15 and 41 shoulder symptomatic patients in their studies, respectively, and good to excellent inter-rater reliability (>=0.7) was observed in both studies. Shin et al. also reported an excellent level of agreement regarding the concurrent validity of the smartphone application (r>0.8) [129].

Mejia-Hernandez et al., [127] also focused on GetMyROM application and compared measurements obtained from this application with a universal goniometer as the gold-standard on 75 patients with

a registered shoulder disease. An excellent inter-rater reliability was reported (>0.95) in this study [127].

Three other studies [128,130,132] assessed the inter-rater or inter-instrument reliability on 10, 30, and 10 healthy participants, respectively. They all reported an excellent inter-reliability level on smartphone measurements in nearly all shoulder motions (ICC>=0.9) [10, 13, 16].

All in all, the results of the six studies indicated that smartphone sensor measurements could be considered as a reliable and valid replacement method for the purpose of shoulder ROM measurement.

Hand ROM:

Two studies evaluated reliability and validity of smartphone sensor applications for the finger ROM measurement in a total of 39 patients with the Dupuytren disease or dealing with hand problems. Miyake et al., [133] evaluated the inter-instrument reliability and validity of an application called EHMROM in comparison to a traditional goniometer. In another study, O'Brien et al., [131] evaluated the reliability and validity of another application called the Measure.

Both studies reported excellent reliability and validity levels (ICC>0.9; r>0.9), and indicated that finger ROM measurements using smartphone sensors could be considered as reliable and valid as conventional goniometry measurements [131,133].

5.4 Discussion

This systematic review demonstrated most of the included studies employing smartphone photography and sensor applications to measure the range of motion (ROM) of the hand and upper extremity joints, reported good to excellent reliability or validity. Fourteen studies were qualified for inclusion in the photography section and 17 studies were included in the smartphone sensor applications section, which evaluated several hand and upper limb joints. In the photography applications, elbow (n=5) was the most evaluated joint, followed by shoulder (n=3), wrist (n=3), and hand (n=3). Various measurement techniques, including mobile applications, selfies, as well as the smartphone's camera, were applied to take photos with a smartphone. The results of the

studies indicated good to excellent reliability and validity for the use of all the applied methods of smartphone photography in measuring the ROM of hand and upper extremity joints. Two studies [24,108] failed to demonstrate sufficient reliability and validity for measuring supination and pronation of the forearm in healthy subjects. In the smartphone sensor category, Shoulder joint (n=6) was the most focused joint, followed by wrist (n=5), elbow (n=4), and hand (n=2). The studies in this section either attached the smartphone to the intended region and started to collect data obtained and presented in an application (commercial or self-developed) of the smartphone. Similarly, the included studies in smartphone sensor application section indicated good to excellent reliability and validity for the use of all the applications in measuring the ROM of hand and upper extremity joints.

Regarding the photography applications, several factors may account for the lower reliability and validity indices of studies for rotational ROM (supination and pronation). The factors include the resolution of the smartphone camera, unclear landmarks, difficulty locating the plane of movement, or lack of professional knowledge (anatomical positions) [134–136]. In the smartphone sensor applications, the static errors of smartphone sensors are higher in the transverse plane than in cardinal planes, which can reduce measurement precision when using smartphone sensors [137,138]. Range of motion assessment necessitates the use of specific movement planes. In comparison to other planes, the transverse plane may provide the best perspective for analyzing wrist ulnar and radius deviations. In addition, frontal plane perspective is required to capture shoulder abduction ROM, whereas the sagittal plane is needed to capture shoulder and elbow flexion and extension ROM.

Over the past two decades, the reliability and validity of photography-based goniometry (using digital cameras) in various joints and pathologies of upper and lower extremities have been evaluated, including elbow contractures [139], knee [95,140], shoulder [141,142], or dorsiflexion in individuals with autism spectrum disorder (ASD) due to Gastrocnemius and Soleus shortening [143]. However, with the passage of time, the reliability and validity of photography-based goniometers using digital cameras or cellphones have increased, allowing clinicians to confidently apply this technique in routine clinical practice. Similarly, Inertial measurement units and accelerometer

sensors have been applied in research studies for obtaining the ROM in various upper limb and lower limb joints [33,43,60]. Through the advancement of smartphone industry, researchers have started to offer novel solutions based on accelerometer and IMU sensors embedded in smartphones.

This systematic review included seventeen studies in both categories conducted solely on healthy subjects and twelve studies on subjects with hand, elbow, or shoulder disorders. However, there was no discernible effect on validity or reliability based on the populations investigated, and we can conclude that the validity and reliability of the measurements are independent of whether the population is healthy.

One of the benefits of incorporating technology (smartphones or other commonly used tech devices) into healthcare delivery systems is that it facilitates telerehabilitation/remote care and improves patient adherence to treatment [144]. Following the COVID-19 pandemic, the need for and importance of online therapy sessions and telerehabilitation surged, and more health care practitioners began to offer remote care to patients [145]. Researchers working in health care, particularly in countries with low/limited resources, need to focus more on the early-stage study of the use of telerehabilitation. Indeed, research on the adoption of telerehabilitation is essential to reducing implementation failure, as it will educate patients and healthcare workers on appropriate adoption strategies [146].

Using smartphones to measure ROM could be beneficial in various ways. First, it could be more reliable than manual goniometry since it depends less on the expertise of the observers and examiner [43]. Moreover, it is something patients can perform at home, which enhances adherence to therapy and bridges the gap between follow-up meetings [147]. Another advantage is that smartphones are now widely available, even to older adults, and are portable. As a result, they could be utilized as an alternative or complement to manual goniometry to facilitate the evaluation process, treatment adherence, and overcoming transportation difficulties [147].

There are a number of benefits to using smartphone-based goniometry, as mentioned by other studies for the knee joint [95], including producing a permanent and printable report; conducting

measurements on the photographs at any time; or recorded sensor data in smartphone applications; facilitating telerehabilitation for patients at home; and improving patient compliance to treatment by providing patients with their ROM data and demonstrating their improvement.

Constraints of using smartphone photography for ROM assessment exist. Technological flaws can lead to erroneous measurements or invalid results [148]. In addition, patients must be given detailed instructions for taking the proper and desired digital photographs [23]. Moreover, taking photos of certain joints, such as shoulder and elbow, mostly requires two individuals to perform the task, and it cannot be guaranteed whether it would be possible for individuals living alone to handle it [109]. One of the other factors that is important is analyzing the digital photographs to report the measurement of ROM. Seven studies in this review analyzed the digital photographs by a computer software. However, the others that used applications for the measurement of ROM, used in-app features to analyze and report the measurement findings. There was no study to compare the findings of these methods and their relative measurement properties. Another barrier to the adoption of smartphone technology is the confidentiality of health information [149]. The output of the ROM should be stored on the encrypted medium. Moreover, the transmission of the information must be protected and established in accordance with the local Personal Health Information Protection Act. Nonetheless, such a confidentiality strategy is not yet in place.

On the other hand, some of the mentioned constraints can be alleviated through smartphone sensor applications. As they do not record pictures of patients and the only recorded data points are angles, they address patient's privacy concerns to a better level. Moreover, using bands or straps and attachment equipment to affix the phone to the interested limbs, the process may be performed individually and the measurements can be self-administrated [120,127,129,132]. Finally, all the analysis and process of the angles have taken place in the smartphone application that eliminated the need for an external processing software. However, there are other types of constraints involved in this category encompassing finding the correct placement location of the phone [150], or the difficulty of calibration processes in some of the applications [42], along with the need for a comprehensive tutorial to teach how to work with a specific application to perform a correct measurement.

Nonetheless, both methods of sensor or photography prove to be useful and advantageous to be used in certain conditions and settings.

We experienced some limitations in our study including the rapid rate of advancement in smartphone technologies. The smartphones that are used in the studies are becoming obsolete, and there is limited evidence on the reliability and validity of the current Android and iOS smartphones.

Overall, the findings of this review, which drew on 29 research studies, support the use of smartphone photography and sensory applications as a reliable and valid approach for upper limb joints' ROM measurement and can be confidently integrated into clinical practice. However, we cannot recommend the best application for ROM measurement or rank one application over another. More research is required to evaluate more recent applications or new smartphones' cameras and establish their advantages. Moreover, it is important to highlight that smartphone (or any other tech device) is not meant to serve as a substitute for healthcare practitioners; rather it is recommended to facilitate and speed up clinical assessments, which of course, depends on the context. In-person assessment and conventional measurement are still faster than smartphone applications or images. Some clinicians do visual estimation instead of using a goniometer [151]. However, in a telerehabilitation session, using photos or developed applications for ROM measurement could be faster and more accurate than the traditional way.

5.5 Conclusion

Smartphone photography and smartphone sensor applications are reliable and valid approaches for the measurement of upper extremity joints' ROM. Digital photography in the included studies in this review was taken by smartphone cameras directly, and mROM, DrGoniometry, and RateFast smartphone applications. Smartphone sensor-based applications also proved to be useful in obtaining the upper limb ROM. However, caution should be taken when using applications for which the evidence of reliability and validity indices is lacking.

5.6 List of Tables

Table 5-1. Summary of the included studies in the Photography applications category

Author, Year	N	M/F	Age (mean/range)	Population	Intervention	Plane of photography	Control	Movement	Index	Result
1. M. Ge, 2020 [18]	38	17/21	45/26-60	DRF	Digital Photography Two series of photographs, surgeon's photography, and patient's photography; ROM was measured using analytic software	Transverse plane	Manual Goniometry	Wrist ROM	Reliability (LOA), Validity (Pearson Correlation)	High agreement and correlation between manual goniometry and digital photography showed no discernible differences between the two techniques. Additionally, there was no discernible difference between the photos captured by patients and surgeons.

2. John Z. Zhao, 2019 [19]	50 (94 contracted fingers)	4:1 ratio	65	Dupuytren fixed flexion contracture (FFC)	Digital Photography (Two series of photographs, trained photos by research staff, untrained photos by patient's family members) analyzed for degree of contracture via software analysis	Transverse plane	Manual Goniometry	degree of contracture	Interobserver reliability (ICC, Pearson correlation), agreement between interobserver measurements (Bland-Altman)	High reliability and accuracy of smartphone photography support its application in clinical and research settings with patients with Dupuytren disease.
3. Reid, S, 2019 [20]	30	7/23	55/22-73	DRF and healthy participants	Digital Photography (DrGoniometer)	Frontal plane	Universal goniometer	Forearm supination	Reliability (inter-rater and intra-rater using ICC, SEM, and $MDC_{90,}$ Bland and Altman), Validity (Pearson correlation)	Using the DrGoniometer app on iPhone devices, participants with DRF, as opposed to healthy controls, demonstrated high reliability and validity. Both approaches showed poor inter-rater reliability in healthy participants.

4. Wagner, E. R., 2018 [21]	32 (64 wrists)	15/17	42/25-68	Healthy participants	Digital Photography; measurements were analyzed using Adobe Photoshop.	Transverse plane	Goniometry	Wrist ROM	Reliability, validity, accuracy	The use of smartphone photography to measure wrist ROM is more reliable, valid, and accurate than conventional clinical goniometry.
5. Keijsers, R., 2018 [22]	40	21/19	48	Healthy participants	Digital photography; Elbow ROM measured using Kinovea sofware	Sagittal plane (flx/ext) and Frontal plane (Sup/Pron)	Movie, smartphone application, and universal goniometer	Elbow ROM	Validity, inter- and intraobserver reliability	Smartphone photography is a reliable and valid approach for measuring elbow flx/ext ROM in comparison to other methods. However, it failed to produce valid results in measuring supination and pronation ROM.
6. Megan A. Meislin, 2016 [23]	32 (64 elbows)	15/17	42/25-68	Healthy participants	Digital Photography; measurements were analyzed using Adobe Photoshop.	Sagittal plane	Surgeon's photograph, and UG	Elbow ROM	interobserver reliability, accuracy, validity	In patients with elbow injuries, smartphone photography is a reliable and valid alternative to surgeon photography and UG.
7. Cuesta-Vargas, A. I., 2016 [24]	37	22/15	54	Healthy participants	Digital Photography (image-based app (mROM)	Frontal plane	inertial sensors	Shoulder abduction	Intra-rater and inter-rater	Using smartphone photography is a reliable and valid method in the measurement of shoulder abduction.

				and shoulder pathology					reliability, validity	
8. Katy Mitchell, 2014 [25]	94	37/57	26.4	Healthy participants	Digital Photography (DrGoniometry)	Sagittal plane	UG; GetMyROM (inclinometery-based)	Shoulder external rotation	Reliability, validity	Both applications are valid and reliable approaches for measuring shoulder external rotation. As it provides representations of landmarks and a record of measurement, photo-based applications have been deemed superior to inclinometery-based ones.
9. Ferriero, G., 2011 [26]	28	-	-	Healthy participants	Digital Photography (DrGoniometer)	Sagittal plane	UG	Elbow ROM	Reliability (intra- and interrater correlation and agreements analysis)	The DrGoniometer application is a reliable means of measuring elbow ROM and can be considered as an alternate or supplementary method to the conventional methods of measuring elbow ROM.
10. Shields MN 2021 [27]	50	32/18	50/23-83	Elbow contractures	Self-taken photographs (‘‘selfies’’)	Sagittal plane	UG	Elbow ROM	intraobserver reliability; Bland–Altman plots	Selfies of elbow flexion–extension can measure elbow range of motion accurately. ROM measures seem unaffected by selfie technique errors. Elbow

										flexion-extension can be measured outside of a clinic visit, increasing follow-up evaluations and decreasing loss to follow-up. The ability of older people to take a usable selfie was inversely correlated with the accuracy and reliability of the measurements.
11. Langton 2020 [28]	53	26/27	-	Healthy participants	RateFast Goniometer smartphone app	Sagittal plane	UG and Protractor (to test the accuracy in the measurement of a predefined angle);	Shoulder flx and ext	interrater reliability; accuracy;	The RateFast Goniometer app generated precise shoulder ROM measurements in both in-person and telemedicine settings.
12. Chen 2021[29]	33 (37 fingers)	23/10		Flexor tendon repair	Digital Photography; ROM was measured using analytic software	Sagittal plane	UG	Finger flx and ext	interobserver reliability; Bland–Altman plots	Finger ROM measurements using smartphone photography, if done correctly, could be considered as reliable as conventional goniometry measurements.

13. Lam 2023	30	12/18	28.9 (18-65)	Healthy participants	Digital marker less motion capture (MMC); ROM was measured using analytic software on iPad pro	Frontal and Sagittal plane	UG	Elbow flx and ext/Shoulder flex and abd	Reliability, validity	The iPad MMC system generally underestimated the shoulder and elbow AROM. This angle inconsistency between the MMC and the goniometry shows that the MMC system might not currently be a good replacement for goniometry in clinical use.
14. Gu 2023	28 (56 hands)	21/7	26.9	Healthy participants	MediaPipe	Frontal and Sagittal plane	UG	Finger flx and ext	interobserver reliability; Bland–Altman plots	In ICC and the Pearson correlation coefficient, 75% of parameters (24/32) achieved excellent or very good correlation, except the MCP joint flexion of the four fingers, which was regarded as questionable correlation (ICC: 0.126, 0.157, 0.209, 0.195). 84% of parameters (27/32) resulted in a Pearson correlation coefficient over 0.6, showing a strong positive correlation
DRF: Distal Radius Fractures; flx: flexion; ext: extension; UG: universal goniometer										

Table 5-2. Risk of bias of the included studies in the Photography applications category based on the modified QAREL criteria.

Author, Year	Representative sample	representative raters	blinded to others' findings	Blinded to own findings	Blinded to results of ref std	blinded to clinical information	blinded to additional cues	order of exam varied	Appropriate time interval	Test applied correctly	Appropriate statistical measures	Y/Other
1. M. Ge, 2020 [18]	Y	Y	Y	Y	Y	NA	NA	UC	NA	Y	Y	63%
2. John Z. Zhao, 2019 [19]	Y	Y	Y	Y	Y	NA	NA	Y	NA	Y	Y	72%
3. Reid, S, 2019 [20]	Y	Y	Y	Y	Y	NA	NA	UC	Y	Y	Y	72%
4. Wagner, E. R., 2018 [21]	Y	Y	Y	Y	Y	NA	NA	N	NA	Y	Y	63%
5. Keijsers,	Y	Y	Y	Y	Y	NA	NA	Y	Y	Y	Y	81%

R., 2018 [22]												
6. Megan A. Meislin, 2016 [23]	Y	Y	Y	Y	Y	NA	NA	UC	NA	Y	Y	63%
7. Cuesta-Vargas, A. I., 2016 [24]	Y	Y	Y	Y	Y	NA	NA	UC	Y	Y	Y	72%
8. Katy Mitchell, 2014 [25]	Y	Y	Y	Y	Y	NA	NA	Y	Y	Y	Y	81%
9. Ferriero, G., 2011 [26]	Y	Y	UC	UC	UC	NA	NA	N	Y	Y	Y	45%
10.	Y	Y	Y	Y	Y	NA	NA	N	NA	Y	Y	63&

Shields MN 2021 [27]												
11. Langton 2020 [28]	Y	Y	UC	UC	UC	NA	NA	N	NA	Y	Y	36%
12. Chen 2021[29]	Y	Y	N	N	N	NA	NA	N	NA	Y	Y	36%
13. Lam 2023	N	Y	UC	Y	N	NA	NA	UC	Y	Y	Y	45%
14. Gu 2023	N	Y	Y	Y	Y	NA	NA	UC	Y	Y	Y	72%
N: No; N/A: Not applicable; UC: Unclear; Y: Yes												

Table 5-3. Methodological quality of validity studies included in in the Photography applications category using Quality Assessment of Diagnostic Accuracy Studies (QUADAS).

Item	QUADS items	1. M. Ge, 2020 [18]	2. John Z. Zhao, 2019 [19]	3. Reid, S, 2019 [20]	4. Wagner, E. R., 2018 [21]	5. Keijsers, R., 2018 [22]	6. Megan A. Meislin, 2016 [23]	7. Cuesta-Vargas, A. I., 2016 [24]	8. Katy Mitchell, 2014 [25]	12. Chen 2021[29]	13. Lam 2023	14. Gu 2023
1	Representative sample	Y	Y	Y	N	N	N	Y	N	Y	N	N
2	Selection criteria	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
3	Appropriate reference standard	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
4	Stability of target condition	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
5	Appropriate sample received reference standard	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
6	Same reference standard to all	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
7	Reference standard independent of the index	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
8	Index test detailed	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

9	Reference standard detailed	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y
10	Independent interpretation of index test	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
11	Independent interpretation of reference standard	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
12	Clinical data available similar to that in practice	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
13	Uninterpretable/intermediate test results reported	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC
14	Withdrawals explained	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC
Y/Other		78%	78%	85%	71%	78%	78%	85%	78%	78%	78%	%78
Y: Yes; N: No; UC: Unclear												

Table 5-4. Summary of the included studies in the Sensor applications category

Author, Year	N	M/F	Age (mean/range)	Population	Intervention	App/Sensor in smartphone	Movement	Index	Result
1. Wassmuth et al., 2020 [117]	43	0/43	20/18-30	Healthy participants	Wrist ROM was measured three times by three blind examiners for the active wrist flexion and extension. The back of the phone was in contact with the dorsal region of the participant's wrist	Goniometer Pro	Wrist ROM	Inter-observer and intra-observer reliability (ICC and 95% CI) Pearson's correlation coefficients	The Goniometer PRO© can be used in clinical practice for the evaluation of the range of motion of the wrists of women, as demonstrated by the excellent intra-examiner and inter-examiner reliability and good level of agreement.
2. Engstrand et al., 2021 [119]	33	16/17	45 (24-75)	Healthy participants	The smartphone is held in palm and Wrist Flexion/extension and radial/ulnar deviation were measured with the forearm fully pronated. (3 measurements on two different days with 4-7 days interval)	The WristCheck app (a custom-made mobile app)	Wrist ROM	Test-retest reliability (ICC) Day to day reproducibility (ICC)	Smartphone app had good reproducibility (ICC mean 0.82, range 0.80–0.88) except for flexion and extension, which had excellent reproducibility (ICC 0.90–0.93), and pronation, which had moderate reproducibility (ICC 0.59).

3. Pourahmadi et al., 2017 [120]	70	38/32	27.5 (18 to 40)	Healthy participants	The back of the smartphone phone was fixated with an elastic band on the dorsal side of the hand and one bottom corner of the phone was placed on the center of the extensor pollicis longus border of anatomical snuff box to measure wrist flexion/extension and radial/ulnar deviation ROM.	Goniometer Pro	Wrist ROM	Inter-observer Reliability (ICC (2, k)) Pearson correlation coefficient for concurrent validity	G-pro© app possesses good to excellent reliability (ICC ≥ 0.73) and concurrent validity with a universal goniometer (r ≥ 0.80) for measuring wrist ROM.
4. Lendner et al., 2019 [118]	171	(50%/ 50%)	45.9 (N/A)	Healthy participants	The back of the iPhone was placed on the back of the hand, with the left bottom corner touching the extensor pollicis longus (EPL) in the anatomic snuffbox. The wrist motions were measured using the pitch (for flexion and extension) and yaw (for ulnar and radial deviation) angles showed on the app.	The gyroscope app (iPhone 4)	Wrist ROM	Difference values, p-values (t-test) and Bland-Altman plot	There was good agreement between the app and goniometer measurements for wrist ROM. The agreement between the methods interpreted through the Bland-Altman plot did not demonstrate any bias inherent to the measurements in flexion, extension, radial deviation, and ulnar deviation moves.
5. Kim et al., 2014 [123]	52	(25/27)	32.3	Healthy participants	The rear surface of the iPhone 4 was secured to the dorsum of the hand using an elastic band, with the left	The Gyroscope application	Wrist ROM	Difference values including mean difference, and p-values (t-test).	The wrist ROM was evaluated in a simpler and as precise as the goniometer

					bottom corner positioned at the center of the extensor pollicis longus border within the anatomical snuff box on the dorsum of the hand	(Acrossair Co, San Francisco, CA)			way using the Gyroscope, for healthy participants.
6. Behnoush et al.,2016 [121]	60	47/13	42.5 (22-72)	Healthy participants	Elbow ROM through flexion, supination and pronation of forearm movements were measured three times.The phone placed along the participants' arms.	Bubble inclinometer-based app	Elbow ROM	Inter-observer reliability (ICC and 95% CI) Pearson's correlation coefficients	High reliability and validity scores were obtained for the smartphone inclinometer application in measuring the active movements of dominant hand elbow joint.
7. Santos et al, 2017 [124]	20 and 20	10/10 and 10/10	52.5 (22 to 75), and 41.5 (21 to 69)	Patients suffering from injury to the hand, wrist, forearm or elbow and healthy participants	An iPhoneTM 5 with and without a selfie stick was used to measure active pronation and supination of forearm by two examiners.	The gyroscope application	Elbow ROM	Inter-observer Reliability (ICC (2, k))	Excellent inter-observer reliability for both smartphone-based methods was observed with an agreement of plus or minus 2°, when a rigorous methodology is used.
8. Pottorf et al., 2022 [122]	83	35/48	N/A (22 to 65)	Healthy participants	Participants started with	Clinometer Version	Elbow ROM	Concurrent validity by Pearson moment correlation	The smartphone and standard goniometer demonstrated strong correlations for both pronation and

					their dominant hand upper extremity at their side and their elbow in 90 ° of flexion and the forearm in a neutral position. Three measurements were obtained for forearm pronation and supination using the smartphone, and the averaged value was used for data analysis.	4.9.2 by Plaincode,		coefficient	supination and good concurrent validity between the application and the goniometer.
9. Vaucla ir et al., 2017 [125]	20	9/11	52(21-74)	Patients with a unilateral healed olecranon fracture	For flexion and supination measurements, patients placed their arm on a table, ensuring the humerus was parallel to the horizontal plane. After zeroing the inclinometer, they maximally flexed the elbow, and the smartphone, mimicking a goniometer, was aligned parallel to the forearm. In cases lacking full extension, the smartphone aligned with maximal extension. Pronation and supination involved patients holding a straightedge, aligning the	Clinometer™ APP (Plaincode, Munich, Germany)	Elbow ROM	Difference values including mean difference, and SEM, and p-values (ANOVA)	Smartphone app is acceptable for outpatient clinic follow-up, as the app provides an easy evaluation of complete elbow ROM and produced likewise results to Xray method for elbow flexion. The app overestimates flexion compared to goniometer and should be used with caution to appreciate patient improvement from previous measurements.

					device with it after zeroing in a truly vertical position.				
10. Werner et al., 2014 [126]	24 and 15	15/9 and N/A	N/A	(24) Healthy participants and (15) Shoulder symptomatic patients	Abduction, forward flexion, External rotation with the arm at the side, external rotation with the shoulder abducted to 90°, and internal rotation with the arm abducted at 90° were measured with the patient supine.	The clinometer (Plaincode Software Solutions)	Shoulder ROM	Inter-observer reliability (ICC and 95% CI)	There is an excellent agreement between a goniometer-based gold standard and the smartphone clinometer application for measurement of shoulder ROM in both healthy subjects and symptomatic patients.
11. Mejia-Hernandez et al., 2018 [127]	75	45/21	46 (24-94)	Patients with a documented current shoulder disease	Active forward flexion, total abduction, active and passive abduction along with active/passive external and internal rotation were measured using a smartphone attached with an armband to the distal section of the humerus for seated movements, then repositioned to the wrist for measurements performed with the participant supine.	GetMyROM (version 1.0.3; Interactive Medical Productions, Hampton, NH, USA), an inclinometry-based app	Shoulder ROM	Inter-observer reliability (ICC and 95% CI)	Excellent reliability was observed for inclinometer-based smartphone app.

12. Shin et al., 2012 [129]	41	20/21	52.7 (19-79)	Unilateral symptomatic patients	The smartphone was fixed at the ventral side of the patient's forearm at the wrist level with a DualFit Armband with the vertical line set to zero. Active and passive forward flexion, abduction, external rotation while the arms are at the sides and at 90° abduction, and internal rotation at 90° abduction were measured	Clinometer-level and slope finder (Plaincode Software Solutions, Stephanskirchen, Germany)	Shoulder ROM	Inter-observer reliability (ICC) Inter-instrument relaibility Pearson correlation coefficient for validity	The reliability of the new smartphone-based method was similar to the classical double-armed goniometric measurements. The PCC analysis showed strong positive correlation between the two methods of measurement including FF, ABD, and IR measurements.
13. Kiatkulanusorn et al., 2023 [130]	10	5/5	23.1	Healthy participants	Three examiners measured 8 human shoulder flexion angles using smartphone device attached to the humorous section of participants in supine position.	The Goniometer Records application (Indian Orthopedic Research Group)	Shoulder ROM	Inter-observer Reliability (ICC (2, k))	An excellent inter-rate reliability level was observed for the smartphone application in all angle range measurements except 135° to 180° range which demonstrated a good reliability level. Authors have stated that the most accurate and reliable goniometric measurement devices, in terms of all error metrics, Smartphone Application for human joint angle measurements.

14. Soeters et al., 2023 [128]	30	8/22	31.4 (23-66)	Healthy participants	The app guides the participants using vocalizing instructions, while the participants holding the phone in their palm and performing the moves.	Peerwell smartphone APP	Shoulder ROM	Inter-instrument Reliability (ICC)	The interrater ICC showed excellent agreement between the observer and app measurements (ICCs >=0.90).
15.Ramkumar et al., 2018 [132]	10	(5/5)	27 (N/A)	Healthy participants	The smartphone was placed in an armband and strapped to the participant's mid-humerus section. Forward flexion, abduction, internal and external rotation moves have been measured.	The SDK (FocusMotion, Santa Monica, CA, USA)	Shoulder ROM	Difference values including mean difference, and p-values (t-test).	The SDK and goniometer did not differ by more than 5° for the average angle of measurement of any of the 4 shoulder motions. This demonstrates the accuracy of the SDK in the measurements of shoulder arcs of motion.
16. Miyake et al., 2020 [133]	20	N/A	49/21-89	Patients undergoing treatment for hand problems	Active and passive flexion/extension of the distal interphalangeal joint (DIPj), proximal interphalangeal joint (PIPj), and metacarpophalangeal joint (MPj) were measured	EHMROM	Finger ROM	Inter-instrument reliability (ICC and 95% CI)	The smartphone-based measurement method had excellent reliability similar to the conventional goniometer-based method.

17. O'Brien et al., 2023 [131]	19	N/A	N/A	Patients with a diagnosis of Dupuytren's disease	The metacarpophalangeal joint (MCPJ), proximal interphalangeal joint (PIPJ) and distal interphalangeal joint (DIPJ) joints were measured by placing the smartphone edge over the dorsal midline phalanx proximal to the joint. The phone was then turned with the joint as the fulcrum, and then rested on the dorsal phalanx distal to the joint	''Measure'' application	Finger ROM	Construct validity by Pearson moment correlation coefficient	The "Measure'' application was observed to be consistent, reliable and in agreement with the traditional goniometry in assessing ring and little finger joint angles in a group of patients with Dupuytren's disease.

Table 5-5. Risk of bias of the included studies in the Sensor applications category based on the modified QAREL criteria.

Author, Year	Representative sample	representative raters	blinded to others' findings	Blinded to own findings	Blinded to results of ref std	blinded to clinical information	blinded to additional cues	order of exam varied	Appropriate time interval	Test applied correctly	Appropriate statistical measures	Y/Other
1. Wassmuth et al., 2020 [117]	N	Y	Y	Y	Y	NA	NA	Y	Y	Y	Y	72%
2. Engstrand et al., 2021 [119]	Y	UC	UC	N	UC	NA	NA	N	Y	Y	Y	36%
3. Pourahmadi et al., 2017 [120]	N	Y	Y	Y	Y	NA	NA	N	Y	Y	Y	63%
4. Lendner et al., 2019 [118]	Y	N	N	N	N	NA	NA	UC	NA	Y	Y	27%
5. Kim et al., 2014 [123]	Y	UC	UC	UC	UC	NA	NA	UC	NA	Y	N	18%

6. Behnoush et al.,2016 [121]	Y	Y	Y	Y	Y	NA	NA	N	NA	Y	Y	63%
7. Santos et al, 2017 [124]	Y	Y	Y	Y	Y	NA	NA	Y	N	Y	Y	72%
8. Pottorf et al., 2022 [122]	Y	Y	Y	Y	Y	NA	NA	Y	UC	Y	Y	72%
9. Vauclair et al., 2017 [125]	Y	N	N	N	N	NA	NA	N	NA	Y	Y	27%
10. Werner et al., 2014 [126]	N	Y	Y	Y	Y	NA	NA	Y	NA	Y	Y	72%
11. Mejia-Hernandez et al., 2018 [127]	Y	Y	Y	Y	N	NA	NA	N	NA	Y	Y	63%
12. Shin et al., 2012 [129]	Y	Y	Y	Y	Y	NA	NA	N	N	Y	Y	63%

13. Kiatkulanusorn et al., 2023 [130]	N	Y	Y	Y	Y	NA	NA	Y	Y	Y	Y	72%
14. Soeters et al., 2023 [128]	Y	Y	UC	Y	N	NA	NA	NA	NA	Y	Y	45%
15.Ramkumar et al., 2018 [132]	N	N	NA	Y	N	NA	NA	N	NA	Y	N	18%
16. Miyake et al., 2020 [133]	Y	Y	UC	UC	UC	NA	NA	N	NA	Y	Y	36%
17. O'Brien et al., 2023 [131]	UC	Y	N	N	N	NA	NA	Y	NA	Y	Y	36%
N: No; N/A: Not applicable; UC: Unclear; Y: Yes												

Table 5-6. Methodological quality of validity studies included in the Sensor applications category using Quality Assessment of Diagnostic Accuracy Studies (QUADAS).

Item	QUADS items	1. Wassmuth et al.,	2. Engstrand et al.,	3. Pourahmadi et	6. Behnoush et	7. Santos et al,	8. Pottorf et al.,	9. Vauclair et al.,	10. Werner et al.,	11. Mejia-	12. Shin et al.,	13. Kiatkulanusor	14. Soeters et al.,	16. Miyake et al.,	17. O' Brien et
1	Representative sample	N	Y	N	Y	Y	Y	Y	N	Y	Y	N	Y	Y	N
2	Selection criteria	N	Y	N	Y	Y	Y	Y	N	Y	Y	N	Y	Y	Y
3	Appropriate reference standard	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
4	Stability of target condition	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
5	Appropriate sample received reference standard	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
6	Same reference standard to all	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

7	Reference standard independent of the index	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
8	Index test detailed	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y
9	Reference standard detailed	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y
10	Independent interpretation of index test	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
11	Independent interpretation of reference standard	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
12	Clinical data available similar to that in practice	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
13	Uninterpretable/intermediate test results reported	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC

14	Withdrawals explained	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC	UC
Y/Other		71%	78%	71%	85%	85%	85%	71%	71%	85%	85%	71%	78%	71%	64%
Y: Yes; N: No; UC: Unclear															

5.7 List of Figures

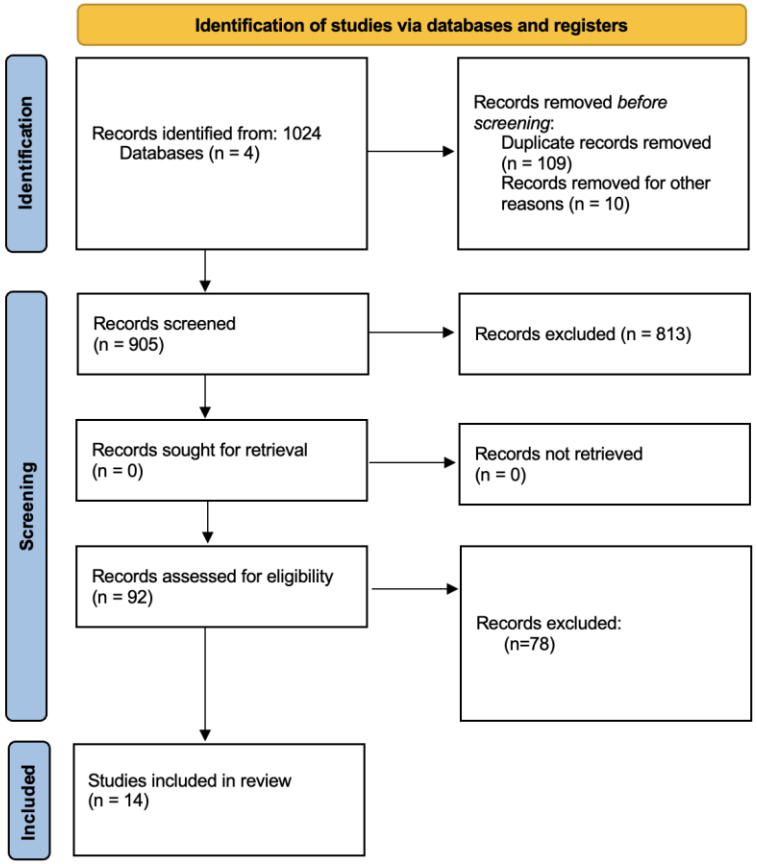

Figure 5-1. PRISMA flow diagram illustrating the selection process for studies included in the systematic review of Smartphone Photography Applications.

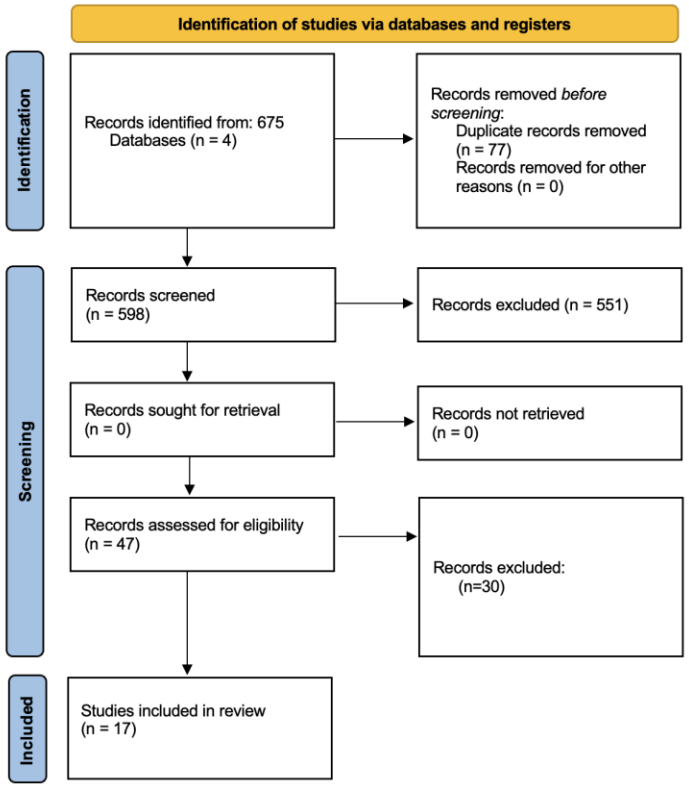

Figure 5-2. PRISMA flow diagram illustrating the selection process for studies included in the systematic review of Smartphone Sensor Applications.

Chapter 6

6 General Discussion and Future Directions

6.1 Overview of this dissertation

In this dissertation, we evaluated different aspects of a novel wearable sensor system called Motion Shirt to track shoulder motions in patients prior to and post-shoulder joint replacement (SJR) surgery. Motion Shirt's validity, consistency, and clinical applicability were assessed and demonstrated in three different studies. The evaluation took place under a standardized context via the Functional Impairment Test-Hand and Neck/Shoulder/Arm (FIT-HaNSA) test. The FIT-HaNSA test is an endurance test that resembles daily life activities, so it was a proper choice for the aim of this dissertation.

In Chapter 2, the validity of Motion Shirt was assessed and proven by comparing the obtained motion outcomes with a pre-validated and reliable system called Dartfish Motion Analyzer software. Through drawing Bland-Altman plots between the results of these two measurements, Motion Shirt demonstrated a high level of agreement with the Dartfish Motion Analyzer in measuring shoulder motion. Our results suggested that the Motion Shirt could be a valuable tool for objectively assessing shoulder motion in patients awaiting shoulder replacement surgery. Moreover, the findings supported the use of Motion Shirt for monitoring shoulder function in the pre-surgical phase of shoulder replacement surgery.

Moving to Chapter 3, the consistency of the proposed Motion Shirt was investigated throughout the shoulder motion measurement period in different axes and tasks of the FIT-HaNSA test. This study was conducted by comparing the odd- and even-numbered sets of motions in each participant and calculating the Intraclass Correlation Coefficient (ICC) results. The results showed that Motion Shirt demonstrated good internal consistency in measuring shoulder movements across different tasks of the FIT-HaNSA test. This suggests that Motion Shirt could be a valuable tool for healthcare professionals to be utilized for better treatment planning and rehabilitation strategies tailored to everyone's needs as it accurately assesses shoulder function in patients with different

conditions undergoing shoulder replacement surgery. However, we also identified challenges, particularly in Task 1 of the test, where compensatory movements were observed. Despite this, Motion Shirt still showed promise in providing consistent measurements, highlighting its potential for enhancing precision and efficiency in shoulder joint function assessments.

Clinical application of Motion Shirt was investigated through a longitudinal study on the cohort of SJR patients in Chapter 4. It aimed to see if Motion Shirt can detect and assess the recovery of the participants after a 6-month period of rehabilitation following their surgeries. The participants were asked to perform the FIT-HaNSA test once before the operation and once after the 6-month rehabilitation period. Motion Shirt successfully presented the recovery pattern in the patients, proving itself as a clinical assessment tool, as notable enhancements were observed in various metrics, including the number of arm movements, promptness, and motion angles, particularly evident during tasks involving movements at waist and shoulder levels. Our study underscores the efficacy of Motion Shirt in monitoring the recovery process post-SJR surgery at home settings, suggesting that patients may experience moderate to substantial improvements in shoulder motion promptness and angle following 6 months of rehabilitation. These findings emphasize the potential of wearable sensor technology to inform and guide the rehabilitation interventions at non-clinical contexts for individuals undergoing SJR surgery.

Moreover, the rising trend of clinical applications in smartphones using their sensors and cameras was evaluated as a future horizon through conducting a systematic review in Chapter 5. The results of this study provide surgeons, clinicians, and physical therapists with high-quality data to support the use of smartphone photography and sensor applications for assessing hand and upper extremity range of motion. The data supported measuring ROM using a smartphone as a legitimate and reliable approach that has great potential to be used in telerehabilitation as an alternative to a hand-held goniometer or inclinometer. Additionally, smartphone-based ROM assessment improves telerehabilitation quality of care through increasing patient commitment to therapy and compliance.

6.2 Clinical and research implications

Motion Shirt's validation, and internal consistency as evidenced by comparisons with established methods such as the Dartfish Motion Analyzer software and comparisons with collected data of participants, indicates its dependability as a tool for objectively analyzing shoulder mobility. The Motion Shirt's potential use in clinical settings is pointed by the resulted validity and consistency of the conducted studies. Notably, individuals with shoulder conditions and patients who are supposed to undergo shoulder replacement surgery and its following recovery period may use the motion shirt to provide more continuous and objective motion outcomes to clinicians. Motion Shirt can help healthcare practitioners monitor patients' shoulder function with better accuracy, enhanced objectivity of outcomes, avoiding personal errors made during conventional measurement methods, facilitating informed treatment decisions, and optimizing personalized rehabilitation strategies.

Task-1 and Task-2 of FIT-HaNSA resembles two different levels of shoulder activity in participants (waist level and above shoulder level, respectively), and its corresponding data reveals significant information about movements at those levels. Collected data in Task-3 also provides useful insights regarding over-head sustained activity. Therefore, each separate task results provided in separate tables throughout the presented studies in Chapters 2 to 4, informs different types of activities and demonstrates Motion Shirt ability in collecting useful, continuous, and objective shoulder motion outcomes for different types of activities. Therefore, the presented results of this dissertation can be used by clinicians to devise personalized rehabilitation plans for patients with shoulder conditions. Moreover, health practitioners and surgeons can specifically detect which type of activities are still problematic for their patients after the surgery at different time points of the recovery. Finally, Motion Shirt may report the motion duration spent at different angle ranges. This point demonstrates Motion shirt's ability in providing a comprehensive clinical monitoring process over the patients while maintaining their privacy (in contrast to cameras recording participants' movements) and avoiding interrupting the daily life activities. Moreover, this ability further informs the clinicians and surgeons about the quality level of activities performed by the patient in his/her home or work settings both prior and after the surgery.

The longitudinal study on SJR patients in Chapter 4, reinforces Motion Shirt's efficacy in monitoring the patients with post-surgery rehabilitation at home settings. Motion Shirt's usefulness as a clinical evaluation tool has been shown through the observed improvements in different measures, such as arm motions, promptness, and motion angles. The collected data imply that Motion Shirt can facilitate the early detection of recovery patterns, allowing for prompt interventions and modifications to rehabilitation programs.

Furthermore, the systematic review study on clinical uses of smartphones utilizing sensors and cameras emphasizes the changing environment of healthcare technology. The findings of the study show the rising trend in the use of smartphone-based assessments to evaluate range of motion (ROM), which provide a simple and reliable alternative to established measurement instruments. This offers up new opportunities for future study into using smartphone technology to improve telerehabilitation user-friendliness, quality of care, eventually improving patient outcomes and therapy compliance.

6.3 Limitations

The studies conducted in this dissertation encountered some limitations. The most significant limitations included a limited number of participants, which restricts the generalizability of results to broader populations and contexts, and also impacts the external validity of the findings. Moreover, the studies took place in a lab context and environment under standardized situations. Although this was necessitated according to the aims of this dissertation, conducting the studies in a non-lab context would have revealed new insights into Motion Shirt’s abilities.

The participants of this study were individuals aged above 50 years old, consenting to participate in the studies voluntarily. This might introduce a volunteer bias in the study as the participants might be healthier, experience less pain in their shoulders, be more educated, or be more socially engaged than non-participants, affecting the generalizability of the results. The participants attended the research lab for performing the tests studies around the time of their clinical routine visits with the surgeons and clinical sessions. Therefore, their endurance for performing the FIT-HaNSA test, as an endurance-based test, might have been impacted due to potential fatigue and

frustration caused by these visits. All in all, we made efforts to ensure their comfort and restfulness for performing the tests by providing enough rest time between tests or inquiring about this matter several times during the studies.

Although we inquired about the comfortability of the Motion Shirt from participants and ascertained it during the studies by providing different sizes of the garment appropriate for each person's shirt size, the wearing time of the Motion Shirt was limited to a maximum of an hour. Therefore, the potential discomfort with wearing the motion shirt for longer periods could not be investigated.

Compensatory movements during the tests can be considered as one of the limitations of the studies, as participants experienced fatigue and increased pain toward the end of the test. They compensated by adjusting themselves to the JOBSIM setting to use a lower reach of their shoulders.

In summary, while these limitations present challenges to the comprehensiveness of the study's findings, they also underscore the complexities inherent in research endeavors.

6.4 Suggestions for the future research

After conducting these studies, several suggestions and ideas are presented as follows:

a) Generalized Cohort: Our studies focused on the population aged above 50. However, the Motion Shirt can be applied for the assessment and monitoring of a more generalized sample. Conducting studies with a broader cohort is highly recommended to enhance the external validity of the Motion Shirt. For example, including younger individuals in future studies might reveal new insights regarding comfortability issues with the Motion Shirt and its adaptability in daily routines for that population.

b) Larger Sample Size: Increasing the number of participants in the studies will enhance the reliability and validity of the new findings. This is due to increasing the statistical power of the studies and reducing the likelihood of false-negative results. Moreover, it will improve precision, providing a clearer understanding of true population parameters and reducing uncertainty. The

impact of outliers and variability within the data will also be mitigated, resulting in more robust conclusions regarding the Motion Shirt's performance. Finally, a more in-depth subgroup analysis can be conducted with a sufficiently large sample size, leading to exploring potential differences in the effectiveness of the Motion Shirt across different subpopulations.

c) Suggestions for the FIT-HaNSA test: According to observations of participants during the test, the arm reach level of individuals highly influences the angles they make for picking up the jars and dropping them off the shelves in Task-1 and Task-2 of the FIT-HaNSA test. Therefore, defining a certain distance between the participant and the JOBSIM setting according to their arm reach level is recommended to ensure similar sets of motions and arcs of motion are performed between participants. Moreover, the positions of jars can be indicated on the shelves, so the participants may accurately place them on the designated spots to enhance the accuracy of performed shoulder motions.

d) Home-based Context: The Motion Shirt is recommended to be developed and applied in studies within home-based contexts. The applicability of the Motion Shirt with long-term use can be assessed and analyzed. In other cases, it can be used for studies suggesting the Motion Shirt be used for home-based rehabilitation exercises and programs. Moreover, interactive exercise modules can be designed to leverage the Motion Shirt data to provide users with real-time feedback and guidance during home workouts. Certain visualizations of shoulder motion angles can be provided to users to help them maintain proper form and technique throughout each exercise repetition.

e) Comfortability Questionnaires: One of the important aspects of the Motion Shirt is comfortability and user-friendliness. This must be investigated through questionnaires and interviews with participants. Moreover, practical clinical challenges with utilizing the Motion Shirt can be inquired about with clinicians and surgeons involved in future studies.

f) Implementing Real-time Feedback: A cautionary feedback in the form of an auditory response or a vibration in the system, or any other form of feedback for users, will further develop the Motion Shirt. This feature can be applied in cases where the user makes an extreme motion with

their shoulder, compromising the recovery process or worsening the current status of their shoulders before surgery.

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7 Appendices

7.1 Letter of Information and Consent form

Project Title: Development of wearables sensors in motion shirts for assessment and rehabilitation of shoulder arthritis and joint replacement

Investigators

Dr. Joy MacDermid, PT PhD (Principal Investigator)

Department of Physical Therapy, Western University

Co-Investigators: Dr. Kenneth Faber &Dr. George Athwal

Hand & Upper Limb Centre, St. Joseph's Health Care

Research Staff and Students: Mr. Erfan Shafiee, Mr. Steve Lu, Mrs. Katrina Munro, Mr. Sohrob Milani Zadeh, Ms. Leila Amirfakhrian

What is the purpose of this study?

You are being invited to participate in this study because you are a patient at the Hand and Upper Limb Clinic of St. Joseph's Hospital. . We are testing whether a new shirt with wearable sensors is a reliable method of measuring every day movements and tracking shoulder movement before and during recovery from surgery. We hope that this shirt will help us to better understand how the rehabilitation and recovery process progresses in shoulder joint replacement patients. We will link biomechanics, motion tracking data, and clinical data obtained from patients to aid in developing a system that provides clinicians and patients with more precise information on their shoulder rehabilitation process. We will also compare data from patients to healthy participants.

Recruitment

Inclusion: Individuals with sufficient capacity to consent, who are aged 50 or over, can speak fluent English and are on the waitlist of shoulder joint replacement surgery.

Exclusion: People who are not generally healthy or they are suffering from a kind of major disease and disability.

Study Procedures

1- You will be provided with comprehensive information about the study and your potential questions will be addressed.
2- If you are still willing to participate, you will sign this consent form.

Pre-op phase:

3- Appointments for data collection sessions will be set up. The sessions will take place at St. Joseph's Hospital in the Hand and Upper Limb Clinical Research Lab.
4- You will fill out a series of questionnaires about your shoulder and everyday life along with some demographic information.
5- A study team member will demonstrate and administer a physical test called the FIT HaNSA where you will be asked to move your arms and hands in different ways.
6- You will wear the motion shirt to do the FIT-HaNSA test while also being video recorded.
7- This visit is expected to take 1 to 2 hours.
8- You will return to the lab in the next 5-7 days to repeat the FIT-HaNSA test for reliability assessment purposes.

Post-op phase:

9- You will return to the lab for a morning visit at 1, 4, 6, 9, and 12 months after your surgery. We will ensure that the shirt fits comfortably and that the sensors are working.
10- You will re-perform the Fit-HaNSA test in the lab that is expected to maximally take 1 hour of your time.
11- You will then keep the shirt on for the rest of the day and go about your normal activities at home and in the community until bedtime when you can take the shirt off. at different times after your operation (). These visits are in the morning. You are supposed to not take off the shirt during your daily life activities until your sleep time. In this regard, the motion shirt will record daily motion activities of you for a day. You can take off the shirt at night.
12- You will mail the shirt back to the lab for analysis using a prepaid envelope.

Participation to the Study:

Participating in this study is voluntary. You will receive a copy of the letter of information and consent form for your records. You do not waive any of your legal rights by signing the consent form. You may refuse to participate, refuse to answer any questions or withdraw from the study at any time with no effect to your future care. You will continue to receive standard care, i.e., routine checkups with your doctor. If you DO decide to stop your participation in our study, we will ask

you how you would like us to handle the data collected up to that point. You have the right to withdraw all data collected for the study. If you have concerns or would like to withdraw, you may contact the principal investigator, Dr. Joy MacDermid or research assistant, Katrina Munro.

What are the benefits of this study?

There are no direct benefits to you associated with your participation in this study. But your study participation will have societal benefits by helping improve knowledge about the recovery process of shoulder arthroplasty surgery.

Are there any risks or discomfort associated with this study?

There is a potential for a privacy breach, as identifying information is being collected. However, identifying information will be kept separate from the data. Instead, the data will be de-identified.

How many people in this study?

There will be approximately 25 people in this study.

Is there any compensation if I participate?

There is no monetary reimbursement for participation in this study. If needed, we can arrange to compensate parking expenses.

Will my results be kept confidential?

Your individual results will be held in strict confidence. No person, other than the study team, treating clinician, Western's Health Sciences Research Ethics Board and its representatives, and Lawson Quality Assurance and Education Program will have access to your identifiable information which will include your name, sex, contact information, and date of birth.

Upon study recruitment, you will be given a unique numerical identifier (Participant ID) that will be entered on all data collection forms containing personal information in lieu of your name. The study investigators will keep a master copy of the unique identifier assigned to each participant.

This list will be stored on the SJHC secure G drive. Your contact information and consent forms will also be collected and stored separately from the master list of unique identifiers. All paper files will be stored in a locked file cabinet in the HULC clinical research lab, and all electronic files will be stored on a password-protected computer on the secure hospital network. A brief summary of this study will be put on our lab website for public viewing; however, this would not identify you in any way. Representatives of the University of Western Ontario Health Sciences Research Ethics Board and Lawson Quality Assurance and Education Program may contact you or require access to your study-related records to monitor the conduct of research and to ensure that proper policies and guidelines are being followed. The studies investigators will retain your identifiable information and study data for 15 years.

Publication

If the results of the study are published, your name will not be used. If you would like to receive a copy of any potential study results, please provide your name and contact number on a piece of paper separate from the Consent Form.

If you have any other questions about your rights as a research participant or about the conduct of the study you may contact: St Joseph's Health Care London Patient Relations Consultant

Consent to Participate In: Development of wearables sensors in motion shirts for assessment and rehabilitation of shoulder arthritis and joint replacement

Investigators:

Dr. Joy MacDermid, PT PhD (Principal Investigator)

Department of Physical Therapy, Western University

- I have read the letter of the information, have had the nature of study explained to me and I agree to participate. All questions have been answered to my satisfaction.

_____	_____	_____
Signature of Participant	Print Name of Participant	Date

My signature means that I have explained the study to the participant named above. I

have answered all questions.

_____	_____	_____
Signature of person obtaining consent	Print name of person obtaining consent	Date

7.2 IMU Sensor Data Collection and Processing for Motion Analysis

This appendix describes the process of collecting and processing data from IMU sensors embedded in the Motion Shirt, leading to the calculation of arcs of motion and angles in the axes of "Elevation" and "Plane of Elevation."

1. Sensor Calibration and Synchronization

The first step involves calibrating the IMU sensors using the calibration wizard in the Yost Labs 3-Space Sensor Software Suite. This ensures that each of the five sensors embedded in the Motion Shirt is accurately configured. Once calibration is complete, the system time is synchronized across all sensors by setting the sensors' time to match the system time. This synchronization is crucial for ensuring that the data collected from each sensor is time-aligned, allowing for accurate analysis.

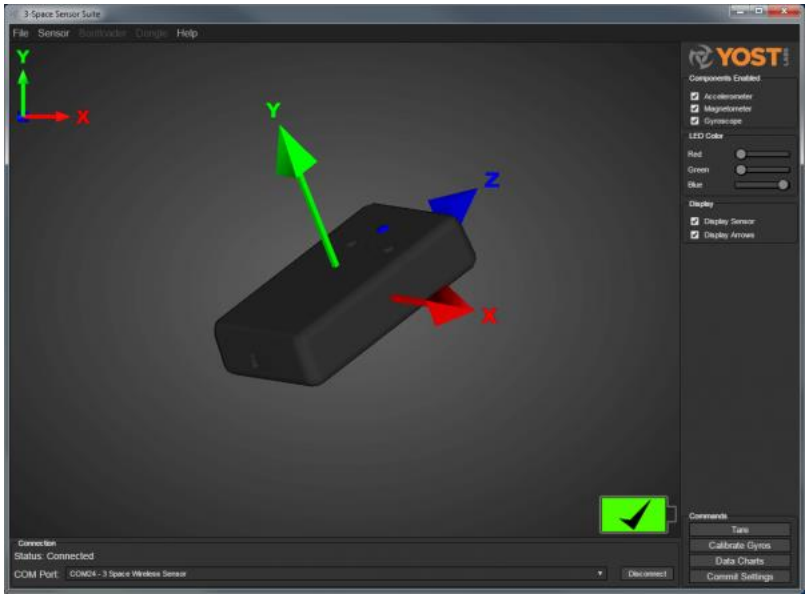

Figure 7-1. the Yost Labs 3-Space Sensor Software Suite

2. Data Recording

After calibration and synchronization, the sensors are placed in their designated sewn pockets within the Motion Shirt. To initiate data recording, the left-side button on each sensor is pressed. The wearer then performs the desired movements, with the sensors actively recording data throughout the task. Upon completion of the movement task, the right-side button on the sensors is pressed to stop the recording. This marks the end of the data collection phase.

3. Data Download and Initial Processing in LabView

The recorded data is then downloaded from the sensors and imported into a custom-developed LabView software application, created by Dr. Langohr et al. Within this application, the data folder is loaded into a designated box, where four angles corresponding to the elevation and plane of elevation for both arms are displayed. At this stage, the general waveform of the collected data can be assessed to inspect for any noticeable noise or motion artifacts. After the data loading process, the LabView software generates a new file containing the recorded angles across different axes and arms for each sample time point.

4. Further Analysis in MATLAB

The final stage of analysis is conducted in MATLAB, where the file generated by LabView is imported into a custom MATLAB script. This script plots each axis's data on separate graphs, allowing for detailed examination. A 3-sample smoothing algorithm is applied to the data to reduce slight noise without significantly impacting the amplitude (less than 1-degree reduction). The plots can be inspected to identify valleys and peaks within the data, and the difference between these points is calculated to determine the arcs of motion.

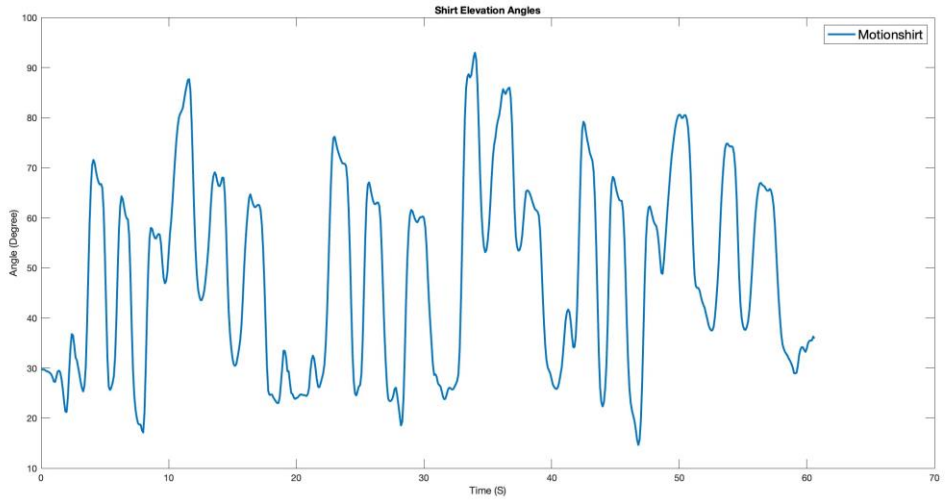

Figure 7-2. MATLAB-imported data for Participant #13 during Task 1, displaying the angles recorded by the sensors along the Elevation axis.

This thorough process of data collection and analysis enables precise measurement of shoulder and arm movements, providing valuable insights into the wearer's motion characteristics. The Motion Shirt's system, combined with advanced processing in LabView and MATLAB, offers a reliable tool for assessing motion in rehabilitation and research settings.

Curriculum Vitae

SOHROB MILANI ZADEH

Education

PhD in Health and Rehabilitation Science **2020 to 2024**
University of Western Ontario, GPA: 90/100
Thesis title: "Development of wearables sensors in motion shirts for assessment and rehabilitation of shoulder arthritis and joint replacement"

- **Shoulder and forearm angles** in two axes of Elevation and Plane of Elevation
- Successfully validated through comparison with Dartfish Motion Analyzer software (Average Standard Error of Measurement**: %2.8)**
- Utilized and applied in a longitudinal study for assessing Shoulder Arthroplasty patients over a one-year clinical period

- Developing a user-friendly User Interface for clinicians to effectively interact with the collected data from the motion shirt using **LabView** and **MATLAB GUI Toolbox**.
- Applied and approved by Lawson and Western University Ethics committees to conduct a clinical trial; recruited 20 patients for conducting longitudinal cohort studies.

Collaborative Specialization in Machine Learning **2022 to 2024 in Health and Biomedical Science** *University of Western Ontario,*

Taken Courses (Grade):

- Introduction Machine Learning (A): Data Analysis (Numpy and Pandas), Data Visualization (Matplotlib, Seaborn, and Plotly), Machine Learning (Linear Regression, Logistic Regression, KNN, Decision Trees, Random Forests, SVM, K-Means Clustering, PCA
- Introduction to Neural Networks (A)
- Machine Learning in Health and Biomedical Sciences (A)

Master of Science in Electrical–Biomedical Engineering **2014 to 2017**
FERDOWSI University of Mashhad (FUM), **GPA: 3.72/4**
Dissertation title: "Design and implementation of Human-Computer Interface using Electrooculography signals with the application of Quadcopter navigation."

- Developing a Human-Computer Interface using **EOG**, and **EEG** signals with the application of Quadcopter navigation in 4 directions.
    - Arduino-based; Using **ADS1299**; 8-Channel (Texas Instruments)
    - PCB Board design using Altium Designer
    - Head Cap design to accurately position 5 electrodes around the eyes using SolidWorks

- **%94.8 Accuracy** of eye movement detection
- **Publication:** https://ieeexplore.ieee.org/abstract/document/9113731

Bachelor of Science in Electrical Engineering–electronics 2010 to 2014
FERDOWSI University of Mashhad (FUM),
Dissertation title: "Linear Estimation of Local Field Potentials in rodents' cortex based on neural activities during Slow-wave sleep"

Official academic tests and courses

GRE: Quantitative: 166/170, Verbal: 151/170, Analytical Writing: 4.5/6
PhD selected courses (grade): Advance Quantitative Research methods (A), Biostatistics (A), Introduction to Quantitative Research Methods (A+)
MSc/BSc selected courses (grade): Computer programming (A-), Special topics of statistics (A)/ Neural networks (A+)/ Engineering mathematics (A), General mathematics II (A+),

Interests

Biomedical Instrument and Sensors (Design and Development)
Health-Data processing
Data Science and Artificial Intelligence

Publications

Published Journal Papers

- MilaniZadeh, S., MacDermid, J., Johnson, J. et al. Applications of wearable sensors in upper extremity MSK conditions: a scoping review. J NeuroEngineering Rehabil 20, 158 (2023).
- Milanizadeh, S., & Safaie, J. (2020). EOG-Based HCI System for Quadcopter Navigation. IEEE Transactions on Instrumentation and Measurement, 69(11), 8992-8999.

In-Review Papers

- MilaniZadeh, S., MacDermid, J., Johnson, J., Langohr, D., Shafiee, E. "Assessing the Validity of a Wearable Shoulder Motion Tracking System, "Motion Shirt" Through Comparison with Dartfish in Patients Undergoing SJR Surgery"
- MilaniZadeh, S., MacDermid, J., Johnson, J., Langohr, D., Shafiee, E. " Assessing the Internal Consistency of the Shoulder Range of Motion Measurement Using a Wearable Motion Tracking System, "Motion Shirt""
- MilaniZadeh, S., MacDermid, J., Johnson, J., Langohr, D. " Assessment of Shoulder Joint Replacement Patients' Motion Outcomes Using a Wearable Sensor System, Motion Shirt: A Six-Month Post-Surgery Evaluation"

- MilaniZadeh, S., MacDermid, J., Johnson, J., Langohr, D., Shafiee, E. “Reliability and validity of using smartphone sensor and photography to measure hand and upper extremity joints range of motion; A systematic review"

Research/Work Experience

Medical Innovation Fellow, *Worldiscoveries department* **2023-2023**
Western University, Supervised by Sarah Hutchison

- Designed a novel device-based treatment method for Migraine (More details are provided upon signing an NDA):
    - PCB Board design using Altium Designer
    - Arduino-based
    - Head Cap design using SolidWorks

Teaching Assistant in Biostatistics, *Western University.* **since 2022**
Supervised by Dr. Ntonghanwah Forcheh

- Courses: Biostatistics, Multiple Regressions, Meta-Analysis, Introduction to Rstudio (study group)

Teaching Assistant in Analytics, *Northeastern University of Toronto.* **since 2022**
Supervised by Dr. Yvonne Leung

- Courses: Database Management Systems, Introduction to Enterprise Analytics, Risk Management for Analytics, Integrated Experiential Learning

Lab Researcher, *McFarlane Hand and Upper Limb Centre (HULC)* **since 2022**
Western University/St.Joseph Health Care, Supervised by Dr. Joy MacDermid

- Designing the motion shirt platform
- Recruiting potential patients and participants for various studies

Product Development Specialist, *FuturU Inc.* **since 2021**
Supervised by Dr. Mehdi Sanjari (CEO)

- Developing a 3D body scanner system, designed to obtain precise measurements and body composition analysis

Lab Researcher, *Visio-motor Laboratory* **2018 to 2019**
FUM Faculty of Science, Supervised by Dr. Ali Asadollahi

- Processing in-vivo extracellular recordings of the cortex during visual, auditory stimuli

Lab Researcher, *BIO Instrumentation Laboratory* **2017 to 2019**
FUM Faculty of Engineering, Supervised by Dr. Javad Safaie

- Classifying awareness using EEG signals through multilayer perceptron neural network
- Missing data Imputation for Breast Cancer data utilizing SVM method

Teaching Assistant in MATLAB, Altium Designer, and Arduino 2014 to 2018
Ferdowsi University of Mashhad, Iran.

Technical Skills

Programming: R, Python (Numpy, Pandas, Scikit-Learn, TensorFlow, OpenCV), R, C/C++)
Software: Rstudio, MATLAB, Altium Designer (PCB Design), SolidWorks (3D CAD)
Platforms: AVR, Arduino, CAD, FPGA
Data Processing: Machine Learning, Signal Processing, Musculoskeletal Biomechanics
Sensors: Inertial Measurement Unit (IMU), Electroencephalography (EEG), Electromyography (EMG), Electrocardiogram (ECG), Electrooculography (EOG), Piezoresistive sensors, Force Plates, Infrared detection

Reviewer for Scientific Journals

Journal of Hand Therapy
BMC Primary Care
Advances in Artificial Intelligence and Machine Learning

Volunteer activities

Western University:
- Leader of the coding study group at Western University focused on learning coding and software programming with R and Python since 2022

PSAC Local 610 (GTA Union):
- **Administration Chair,** - Served as supervisor of the office staff and management of benefits provided to TA members (2023-2024).
- **Financial Assistance Committee Chair,** - Served as the chair of Financial Assistance committee to provide emergency benefits to TA members (2022-2023).

Morrissette Accelerator Program, Ivy Business School:
- **Cohort 2022** – Received funding from the institute to complete business fundamentals courses and to develop the business strategy and growth plans for FuturU Inc., under the supervision of Dr. Eric Morse (2022-2023).

Ferdowsi University:
- Founder member and Secretary of the Biomedical Engineering students' scientific association of FUM from 2014 to 2015
- Associate of IEEE student Branch of FUM from Jan 2011 until Present time