DEPARTMENT OF PHYSICS

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Master/BSc of Science in Biomedical Engineering

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MASTER IN BIOMEDICAL ENGINEERING

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This document was created with the (pdf/Xe/Lua)LaTeX processor and the NOVAthesis template (v7.1.18) [1].

Acknowledgements

First and foremost, I would like to express my gratitude to my supervisor, Arndt-Peter Schulz, for his constant guidance and support throughout my work in the clinic. Your knowledge, advices and sense of humor have shaped my work and made this journey more fulfilling. I am equally grateful to Nils Weinrich for his invaluable assistance during the entire recruitment process and administrative tasks and for always being available whenever I needed support. I would like to extend special thanks to Tobias Barth, Matthias Münch and Birgit Kowald. Working with you in the biomechanics lab was a privilege. Not only did you offer technical expertise and guidance, but your daily support and readiness to find answers to my questions made a huge difference in the challenges I had throughout my work. I am also grateful to Aaron Höing for assisting me with the experimental work. Your company and help were essential in keeping me motivated during the less exciting moments that a project of this magnitude inevitably brings. Thank you as well to the entire physiotherapy team at BG Klinikum, who always welcomed me with a smile, ready to help and excited about my project. Without your support, this work would not have been as meaningful. I would also like to extend my heartfelt thanks to my co-supervisor, Cláudia Quaresma, for her constant availability and for always being there to answer my questions online, no matter the time or complexity. On a more personal note, I would like to thank my family for being always there for me and making me feel always calm and supported in more stressful times. Thank you for believing in me and for never doubting my worth and what I'm capable of doing. I could not be happier knowing how proud I am making you feel. Max, a special thank you to you. Walking this path together in Hamburg has been incredibly meaningful. Your emotional support, constructive advice and, most importantly, your presence by my side during the ups and downs of this journey was invaluable. Finally, to my dear university friends, Leonor Almeida, Ana Pereira, Mariana Falcão and Mariana Seabra, thank you for being my academic family. We have shared both the best and toughest moments of this journey and your friendship, shared wisdom, and patience have been invaluable. I could not have made it here without you by my side. To all of you, thank you for being part of my journey. This achievement is as much yours as it is mine, because I could never have reached this point alone.

Abstract

Accurate measurement of hand mobility is essential for clinical assessments and rehabilitation in physiotherapy. Yet, traditional tools like the goniometer often face significant challenges in terms of repeatability and precision. This inconsistency impacts clinical outcomes and the effectiveness of rehabilitation efforts, emphasizing the need for more reliable methods. An inter-rater reliability study conducted with physiotherapists from BG Klinikum highlighted these limitations, revealing discrepancies between therapists using the same goniometer when measuring patients' Range of Motion (ROM). To address these issues, this study compares the performance of the goniometer, which typically has a variability of two to seven degrees, with advanced measurement technologies. Specifically, an Inertial Measurement Unit (IMU)-based glove developed by the portuguese company Nuada and an Infra-Red (IR) camera system commercialized by UltraLeap were evaluated. These technologies offer advantages over traditional methods, including reduced time consumption, digitized results and more reliable, continuous data.

The methodology involved a comparative analysis of both repeatability and accuracy across both systems. Results showed that both devices demonstrated high repeatability, with an overall standard deviation below two degrees for 43 out of 45 measurements with the Nuada glove and 12 out of 15 measurements with the UltraLeap. Despite their strong repeatability, both instruments encountered challenges with accuracy. Only seven out of 18 measurements taken with the Nuada glove and goniometer showed minimal average differences, compared to three out of 18 measurements taken with UltraLeap and the goniometer.

This study highlights that advanced measurement tools, such as the Nuada glove and the UltraLeap system, can achieve consistent, repeatable results indicating their potential to replace goniometers in clinical settings. However, further work is needed to improve their accuracy and fully establish these technologies as reliable alternatives to traditional mobility measurement instruments.

Keywords: Goniometer, Hand Assessment, Data Glove, Range of Motion, Joint Measurement, Rehabilitation, Mobility, Validation

Resumo

A medição exacta da mobilidade da mão é essencial para as avaliações clínicas e reabilitação em fisioterapia. No entanto, ferramentas tradicionais, como o goniómetro, enfrentam frequentemente desafios significativos em termos de repetibilidade e precisão. Esta inconsistência tem impacto nos resultados clínicos e na eficácia dos esforços dos fisioterapeutas, enfatizando a necessidade de métodos mais fiáveis. Um estudo de fiabilidade inter-avaliadores com fisioterapeutas do BG Klinikum evidenciou estas limitações, revelando discrepâncias entre terapeutas que utilizaram o mesmo goniómetro para medir a amplitude de movimento dos pacientes. Para resolver estas questões, este estudo compara o desempenho do goniómetro, que apresenta uma variabilidade de dois a sete graus, com tecnologias de medição avançadas. Foram avaliados uma luva baseada em sensores inerciais, desenvolvida pela empresa portuguesa Nuada, e um sistema de camera de infravermelhos, comercializado pela empresa UltraLeap.

A metodologia envolveu uma análise comparativa da repetibilidade e precisão de ambos os sistemas. Os resultados mostraram que ambos os dispositivos apresentaram uma repetibilidade elevada, com um desvio padrão global inferior a dois graus em 43 das 45 medições com a luva Nuada e em 12 das 15 medições com o UltraLeap. Apesar da sua alta repetibilidade, ambos os instrumentos enfrentaram desafios de precisão. Ao comparar a luva Nuada com o goniómetro, apenas sete das 18 medições realizadas apresentaram diferenças médias mínimas entre os dois dispositivos. No caso do UltraLeap, essa correspondência ainda foi menor, com apenas três das 18 medições a mostrar diferenças mínimas em relação ao goniómetro.

Este estudo destaca que instrumentos de medição avançadas, como a luva Nuada e o sistema UltraLeap, obtêm resultados consistentes e repetíveis, indicando o seu potencial para substituir os goniómetros em contextos clínicos. No entanto, é necessário um trabalho adicional de modo a melhorar a precisão e refinar estas tecnologias como alternativas fiáveis aos instrumentos tradicionais de medição de mobilidade.

Palavras-chave: Goniómetro, Avaliação Funcional da Mão, Luva Sensorial, Amplitude de Movimento, Medição Articular, Reabilitação, Mobilidade, Validação

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Acronyms

3D three-dimensional *(pp. 9–11, 13, 18, 24, 34)*

AAROM Active-assisted Range of Motion *(p. 5)*
AROM Active Range of Motion *(pp. 5, 21)*

BA Bland-Altman *(pp. 7, 30)*

CM Carpometacarpal *(pp. 3, 4, 24)*
CT Computer Tomography *(p. 6)*

DFKI Deutsche Forschungszentrum für Künstliche Intelligenz *(p. 19)*
DIP Distal Interphalangeal *(pp. 16, 28, 30, 31, 34, 37)*
DP distal phalanx *(p. 22)*

FFCB Finger Flexible Composite Board *(p. 10)*
FNTD fingernail table distance *(p. 21)*
FPD fingernail palm distance *(p. 21)*

HMD Head-Mounted *(pp. 18, 19)*

ICC Intraclass Correlation Coefficient *(pp. 6, 21, 27, 34)*
IMMU Inertial and Magnetic Measurement Unit *(p. 11)*
IMU Inertial Measurement Unit *(pp. iii, 9–12, 16, 18, 35–37)*
IP Interphalangeal *(pp. 3, 4, 22, 28)*
IR Infra-Red *(pp. iii, 2, 9, 13, 14, 18, 37)*

LEDs light emitting diodes *(pp. 13, 18)*
LMC Leap Motion Controller *(pp. 13, 14, 36)*
LoA Limits of Agreement *(p. 7)*

MCM Motion Capture Mainboard *(p. 10)*
MCP Metacarpophalangeal *(pp. 3, 4, 24, 28, 30, 31, 34, 35, 37)*
MCU Microcontroller Unit *(p. 11)*
MP middle phalanx *(pp. 22, 26)*

PIP Proximal Interphalangeal *(pp. 16, 30, 31, 34, 35, 37)*
PROM Passive Range of Motion *(p. 5)*

QTM Qualisys Track Manager *(p. 14)*

RC Radiocarpal *(p. 3)*
RFS resistive flex sensors *(pp. 11, 12)*
ROM Range of Motion *(pp. iii, 5, 6, 10, 12–16, 20, 27, 34, 37)*

SL Scapholunate Ligament *(p. 20)*
SLT Scapholunate Triquetral Ligament *(p. 20)*

TFCC Triangular Fibrocartilage Complex *(p. 20)*

USB-C Universal Serial Bus Type-C *(p. 17)*

VR virtual reality *(p. 18)*

1 Introduction

1.1 Context and Motivation

Beyond their anatomical function, our hands play a crucial role in shaping daily experiences, such as maintaining independency in our activities [2]. Therefore, an effective hand function is needed. However, the vulnerability of our hands to injury, illness and various medical conditions can lead to a feeling of restriction and pain for those affected.

The limitations in hand function often manifest from various sources, ranging from neurodegenerative conditions like ALS and Parkinson's [3] to neuro-cardiovascular events such as strokes. Autoimmune inflammatory conditions such as Guillain-Barre Syndrome, which causes acute flaccid paralysis [4], Rheumatoid Arthritis, a disease that has a specific tendency to induce pain, deformities and functional restrictions [5], age-related issues including sarcopenia and traumatic injuries contribute to the challenges individuals face in preserving and restoring their hand function. In fact, despite a decline, hand injuries remain the leading workplace injury. Specifically, in 2021, according to the German Social Accident Insurance, over 236,681 non-fatal work-related hand and wrist injuries occurred, leading to work absences longer than four days [6]. Moreover, hand and wrist injuries account for about 20% of emergency visits, resulting in a significant economic pressure [7].

Confronting these challenges, physiotherapists undertake the responsibility to provide a pathway to recovery and an improved quality of life. By assessing and measuring hand function, they can customize treatments based on the outcomes and recognize any improvements. Hence, the motivation for this dissertation is driven by the goal of facilitating the demanding responsibilities carried by physiotherapists. It looks at how technology can support physiotherapy and patient care by accelerating assessment procedures, minimizing measurement errors and optimizing the rehabilitation process.

1.2 Objectives

In the context of advancing technology in healthcare, a device for the digital measurement of hand function is currently under development by a Portuguese start-up named Nuada [8]. This innovative device aims to significantly simplify and improve the efforts of physiotherapists and medical doctors when assessing hand and wrist disabilities following diseases or injuries.

Hand physiotherapists traditionally invest considerable time, up to 45 minutes, in manually determining a patient's hand function through a series of joint angle assessments using standard instruments, as the goniometer [9]. This process involves documenting findings with pen and paper or inserting them manually in the computer. This inefficiency not only consumes valuable time but also reduces the ability of therapists to spend time directly interacting with their patients during therapy sessions. Moreover, the inherent variability of the goniometer, ranging from two to seven degrees [10], can introduce discrepancies in assessments as well as measurements of one patient taken by different therapists can also have deviations from each other [10]. Therefore, having an instrument like this one would reduce concerns regarding discrepancies between raters, as the potential error would be consistent across measurements, ensuring uniformity in assessment regardless of the therapist conducting the evaluation. The Nuada sensor glove, an innovative creation of Nuada, presents a promising solution.

This study aims to explore whether this existing glove's prototype can efficiently and accurately assess hand function, particularly hand mobility, presenting a lower variability while digitally documenting each patient and measurement in real-time. The validation process, conducted at BG Klinikum in Hamburg, will determine whether the glove can reliably assess joint mobility with a high repeatability and accuracy. In addition to this sensor glove, two other measurement instruments: an IR camera system and a potentiometer-based glove will also be evaluated, with the aim to allow an approximate determination of the Nuada's accuracy in comparison to other methods. Their repeatability will be assessed and compared with the Nuada's glove to determine the most reliable tool for measuring hand mobility.

1.3 Theoretical Concepts

1.3.1 Anatomy of the hand

1.3.1.1 Osteology

The hand and wrist, consisting of 27 bones, offer a wide range of movements. Divided into three regions – the carpus (wrist), metacarpus (palm) and phalanges (fingers) [11].

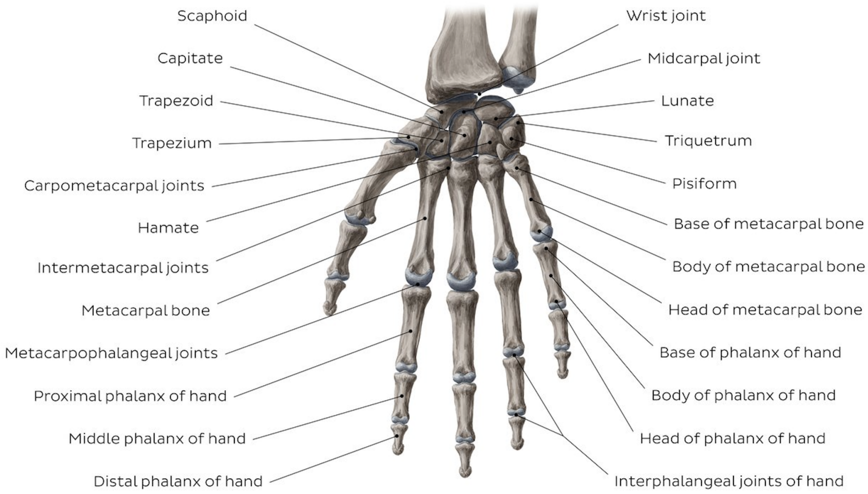


Figure 1.1: Overview of the bones of the wrist and hand [11]

The carpus, formed by eight carpal bones of the wrist, serves as an essential link connecting the radial and ulnar bones in the forearm to the five metacarpal bones in the hand [12]. These carpal bones confer flexibility to the wrist and are distributed into proximal and distal rows, with the pisiform, triquetrum, lunate and scaphoid forming the upper row and the hamate, capitate, trapezoid and trapezium forming the lower row [13], each with specific articulations and functions. Transitioning to the metacarpus, the hand's central segment consists of five metacarpals, articulating with each other and various carpal bones, providing stability and mobility. Each metacarpal bone is associated with a particular digit: the first metacarpal with the thumb, the second with the index finger, the third with the middle finger, the fourth with the ring finger and the fifth with the small finger [14]. Each bone is formed by a head, body and base. The proximal bases of the metacarpal bones articulate with the carpal bones, creating the Carpometacarpal (CM) joints, while the distal heads articulate with the proximal phalanges, forming the Metacarpophalangeal (MCP) joints [15]. Finally, the phalanges, 14 long bones forming the fingers, each composed of a distal, middle and proximal phalanx, except for the thumb, which has only a distal and a proximal phalanx [16]. Furthermore, the head of the proximal phalanx articulates with the base of the distal phalanx, creating the Interphalangeal (IP) joint [14].

1.3.1.2 Joints, Ligaments and Muscles of the Wrist and Hand

The wrist presents two degrees of freedom and when combined with the forearm's pronation and supination, allowing rotation along its axis, it enables the hand to achieve various orientations for grasping or holding objects [13]. The important hand joints, illustrated in Figure 1.2, enable movement in diverse ways. The Radiocarpal (RC) joint connects the forearm to the hand, allowing for versatile flexion-extension and abduction-adduction movements. Adjacent to it, the midcarpal joint complements these motions with gliding articulation between the carpal bones. Moving into the hand, the CM joint of the thumb enables intricate movements like circumduction and opposition, while those of the fingers primarily facilitate flexion-extension. MCP joints offer a wide range of finger mobility, including flexion, extension, abduction, adduction and circumduction. Lastly, the IP joints, serving as simple hinges, allow for essential flexion movements. Together, these joints form a sophisticated system vital for the hand's remarkable agility and functionality [13].

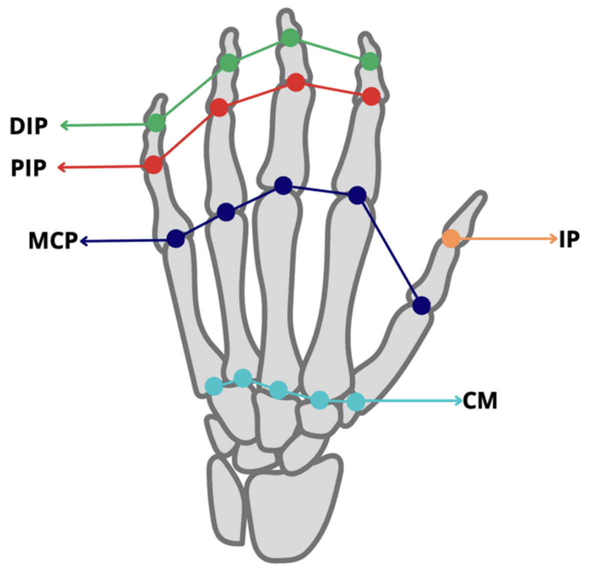


Figure 1.2: Structure of hand joints

To facilitate joint movement, ligaments, essential rope-like tissues that connect bones, provide crucial stability and maintain alignment within synovial joints. In the hand and wrist, a complex network of ligaments, including collateral ligaments, the volar plate, radial and ulnar collateral ligaments, volar and dorsal radiocarpal ligaments and ulnocarpal and radioulnar ligaments, ensure stability while limiting excessive motion. These ligaments prevent sideways movement and hyperextension, supporting both the palm and back of the wrist. Additionally, the flexor retinaculum forms the carpal tunnel, assisting in wrist stability by accommodating nerves and tendons. Overall, these ligaments are vital for preserving the structural integrity and functionality of the hand and wrist joints. While ligaments facilitate movement, muscles serve as the primary agents of motion through contraction. Innervated by the radial, median and ulnar nerves [17], hand and wrist muscles can be categorized into intrinsic muscles, responsible for precise movements originating within the hand and extrinsic muscles, driving more general movements originating from the forearm [18], [19].

1.3.2 Assessment of the Range of Motion

The ROM is a crucial aspect of assessing joint flexibility, function and overall musculoskeletal health. It refers to the total movement a joint can achieve and can be divided into three types: Passive Range of Motion (PROM), where an external force causes the movement; Active-assisted Range of Motion (AAROM), where an external force provides partial assistance; and Active Range of Motion (AROM), where the movement is performed without any external force [20], [21].

As mentioned previously, various factors can limit the ROM, including medical conditions associated with a limited joint motion, fractures, inflammation, pain and various more. To accurately assess these changes, clinicians utilize goniometers, instruments designed to measure joint angles. Among the different types, the universal goniometer is the most commonly used in clinical settings, divided into two versions: the long-arm goniometer, suited for measuring larger joints such as the knee or hip, and the small-arm goniometer, ideal for assessing smaller joints like those in the hand and wrist. The goniometer is positioned as shown in Figure 1.3, with one arm parallel to the static bone before the joint being measured (in red), while the other arm follows the adjacent bone, which moves during the assessment (in green) [22].

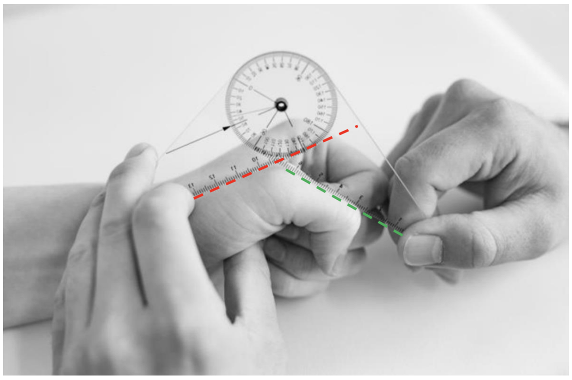


Figure 1.3: Small-arm goniometer [23]

A typical goniometer consists of three main components: the body, which features a scale for angle measurement; the fulcrum, located at the center of the body, allowing the goniometer's moving arm to rotate freely; and the arms, comprising a stationary arm and a moving arm [9].

Although being the clinical standard for assessing ROM [24], it is very time consuming, as it requires measuring one joint at a time. Furthermore, its accuracy depends on the rater's experience and inter-rater reliability tends to be low and inconsistent over time [25]. Indeed, employing a goniometer introduces a level of complexity, considering some aspects: the patient, the specific joint, the goniometer itself and the therapist. This complexity is further emphasized by joint-specific variations, which can explain the variability of universal goniometers, ranging from two to seven degrees in hand joint angle measurements [10]. Also, research in the literature has consistently supported the widely accepted measurement error margin of five degrees for goniometric assessments of hand joints [26]. The demonstrated variability underscores the potential challenges and significant differences that may arise when using a goniometer in the assessment process [27].

1.3.3 Analysis methodologies and applied statistical methods for the validation of instruments

From the beginning, it was evident that directly evaluating against the ground truth would not be feasible. Determining directly the ROM of a patient's hand and finger movements would require invasive methods, such as a Computer Tomography (CT) scanning or serial x-rays. Since these invasive methods do not provide any significant benefit to the patient, they are considered ethically unacceptable due to the unnecessary burden they impose. Consequently, the decision was made to first establish the accuracy of the current standard method, manual measurement with a goniometer, by assessing inter-user variability using the Intraclass Correlation Coefficient (ICC). The rationale behind this approach was that any new method exhibiting measurement deviations equal to or better than this gold standard would be considered acceptable. Additionally, a highly accurate mechanical-electronic measurement device was employed for further validation.

Validating measurement instruments is crucial to ensure their reliability and accuracy, confirming their suitability for its intended use. Reliability can be demonstrated through repeatability, which assesses how consistently an instrument produces the same results under identical conditions [28], [29], often indicated by the standard deviation (smaller standard deviations reflect higher repeatability). Accuracy, on the other hand, refers to how close a measurement is to the true value [30]. This is calculated using comparison methods, which researchers use to validate new instruments by comparing them to established reference methods, often referred to as the gold standard [31]. This assessment can be quantified using various statistical methods, commonly used in medical contexts [32], clarified in the subsequent subsections.

1.3.3.1 Intraclass Correlation Coefficient

The ICC is a widely utilized statistical tool in medical research and clinical settings, serving as a reliability index for evaluating the consistency and agreement of measurements, whether taken by different raters (inter-rater reliability) or by the same instrument under varying conditions (intra-rater reliability). This reliability is crucial for ensuring the validity and reproducibility of medical research findings [33]. When encountering ICC values in literature, below 0.50 signifies poor reliability, 0.50 to 0.75 suggests moderate reliability, 0.75 to 0.90 implies good reliability and over 0.90 indicate excellent reliability [34].

1.3.3.2 Friedman's Test

The Friedman's test is a non-parametric statistical test used to analyze whether there are statistically significant differences between three or more dependent samples, meaning the values are connected. It is the non-parametric counterpart to the analysis of variance (ANOVA) with repeated measurements, being particularly useful when normal distribution is difficult to prove, especially with small sample sizes. This test evaluates differences in the rank totals of repeated measures across different conditions, using rank sums instead of mean differences, which allows the data to not be normally distributed [35]. The hypotheses for it are as follows: the null hypothesis (H0) states that there are no significant differences between the dependent groups, while the alternative hypothesis (H1) states that there is a significant difference between the dependent groups. To interpret the results, the p-value is used to determine whether any of the differences between the values/means are statistically significant. It is compared to the significance level (usually 0.05): if the p-value is greater than 0.05, it indicates no significant difference between the groups; if the p-value is 0.05 or less, it indicates a significant difference between the groups [36]. The calculation of the Friedman's test can be performed using statistical software, which will compute the necessary ranks and p-values to assess the hypotheses.

1.3.3.3 Wilcoxon Mann-Whitney U-test

A Mann-Whitney U-test is the non-parametric counterpart for the t-test for independent samples and tests whether there is a difference between two independent samples. However, while the t-test for independent samples tests whether there is a mean difference, the Mann-Whitney checks whether there is a rank sum difference. In this way, the data does not need to be normally distributed. The hypotheses for the Mann-Whitney test are as follows: the null hypothesis (H0) states that in two samples, the rank sums do not differ significantly, while the alternative hypothesis (H1) states that in two samples, the rank sums differ significantly. To interpret the results, the p-value is also used to determine whether any of the differences are statistically significant [37].

1.3.3.4 Bland-Altman Method

In modern clinical validation tests, it is a frequent practice to evaluate the concordance between two quantitative measurement methods. The Bland-Altman (BA) method is widely employed in assessing the agreement of medical instruments by verifying the mean difference and setting predetermined Limits of Agreement (LoA) based on clinical necessity [38], [39]. It consists of the BA scatter plot, which compares the difference between the two paired measurements (A-B) (Y axis) with the average (A+B)/2 of the measures (X axis) [39], [40]. BA recommended that 95% of data points should reside within ± 1,96s (being s the standard deviation) of the mean difference [40], [41]. Figure 1.4 illustrates a BA plot, which features three key lines. The central horizontal line represents the average difference between measurements from the two instruments, commonly referred to as the "bias." This bias indicates the average extent to which one method over- or underestimates the other. Therefore, the closer the bias is to 0, the more similar the measurements are between the two methods. Additionally, the plot includes the upper and lower limits of the 95% confidence interval for this average difference [42]. These lines provide valuable insights into the typical range of agreement between the two instruments. A broader confidence interval indicates a wider range of differences in measurements, highlighting the variability between the instruments. Understanding this variability is crucial for assessing the reliability and consistency of the measurements.

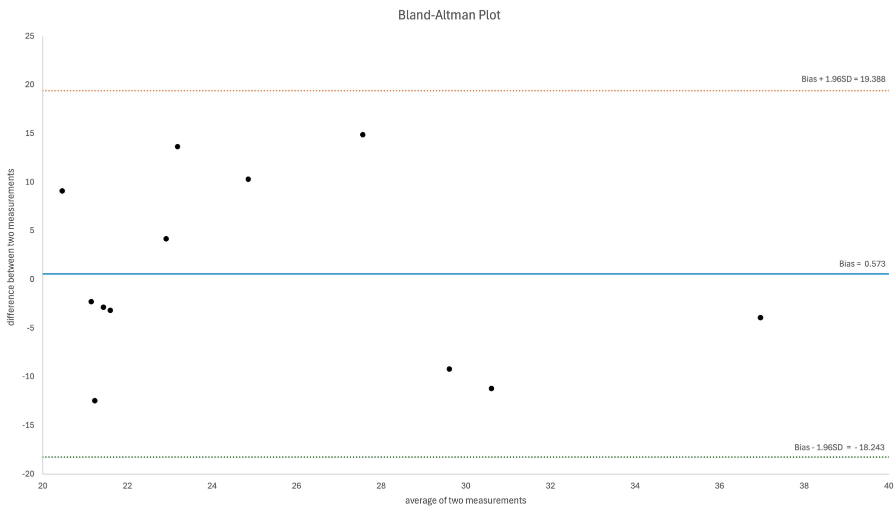


Figure 1.4: Example of a Bland-Altman scatter plot

2

State of the Art

2.1 An instrumented glove for monitoring hand function

Recent studies show a growing development of motion capture devices and sensor-integrated devices for monitoring hand rehabilitation, as they have the potential to improve the way of assessing the effectiveness of rehabilitation, being less time-demanding for both the therapist and the patient. The integration of various sensor types, including optical fiber, IMUs, mechanical and resistive into data gloves, indicates the impact of technological progress on capturing hand kinematics [43], as well as the use of IR cameras, which offer a non-invasive and highly accurate method for evaluating joint movement [44].

2.1.1 Inertial Measurement Unit-based Gloves

An IMU is a sensor device that integrates multiple sensors to measure an object's velocity, orientation and gravitational forces [45], being one of the most widely adopted sensors for sensory gloves [46] due to its lightweight, low cost and accessibility [47]. The accelerometer measures linear acceleration, allowing the sensor to detect changes in velocity or movement of the glove in three-dimensional (3D) space. The gyroscope measures the rate of angular velocity around each axis, providing data on how fast the glove is rotating. Lastly, the magnetometer measures the direction of the magnetic field, which can be used to determine the glove's orientation relative to the Earth's magnetic field.

To obtain angles from the IMUs in the data glove, a proprietary sensor fusion algorithm is employed, which combines data from the accelerometer, gyroscope and magnetometer to calculate the glove's orientation. Common representations include Euler angles, quaternions and rotation matrices. While Euler angles describe orientation by rotations around three axes: roll (ϕ) around the X-axis, pitch (θ) around the Y-axis, and yaw (ψ) around the Z-axis, quaternions provide a representation of orientation using a scalar part and three imaginary parts. From the quaternion data provided by the IMUs, angles representing the glove's orientation can be derived using mathematical operations, through techniques such as quaternion-to-Euler angle conversion, which obtain the desired orientation angles

[43].

Within this field, Bor-Shing Lin et al. [43] developed a data glove based on a modular design with 18 nine-axis IMU sensors on the fingers, wrist, and forearm, as shown in Figure 2.1, facilitating the replacement of components in case of malfunction. Each one of these sensors features a magnetometer, a gyroscope, accelerometer, allowing it to capture data on acceleration, angular velocity and magnetic fields. To ensure the IMU sensor obeys its specifications, a calibration process is needed. Therefore, accelerometer and gyroscope are calibrated by averaging 1000 raw data measurements while magnetometer calibration involves an eight-shaped rotation to determine the maximum and minimum values, which are averaged to find the magnetometer offset.

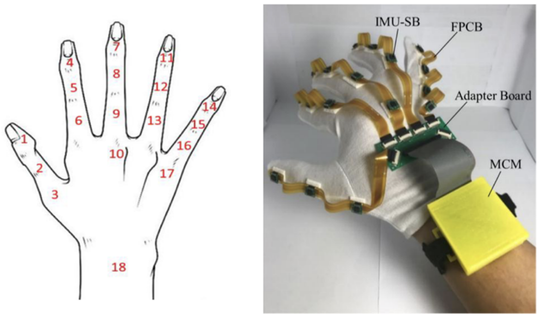


Figure 2.1: Prototype of the proposed IMU-based glove [43]

The glove uses a sensor fusion algorithm, which combines the data collected from the glove, processes the raw data and creates a more accurate and reliable outcome [48] while converting it into interpretable ROM values. The data is then transmitted to the host system via Bluetooth for further processing and display. It is designed for easy wearability, with a prototype featuring a 3D-printed shell for the Motion Capture Mainboard (MCM) worn on the forearm and fastened using Velcro. The Finger Flexible Composite Board (FFCB) and the adapter board are connected to a cotton glove for firm attachment and easy removal [43].

The accuracy of both static and dynamic measurements was possible by using a platform that allowed the bending of one finger at specific angles, as seen in Figure 2.2.

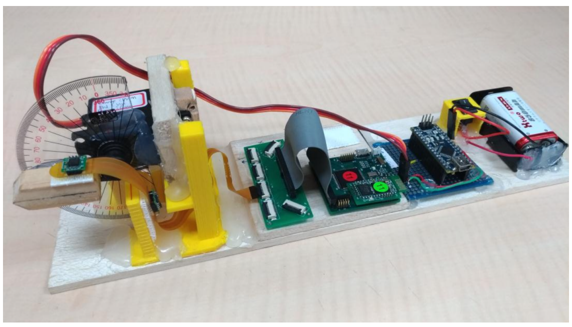


Figure 2.2: Platform for measuring the sensor's accuracy and repeatability [43]

The results indicate that the proposed data glove exhibits a mean angle error of ±3 degrees during motion. For rehabilitation tasks and hand function assessments, this level of error remains acceptable to physicians [43]. However, the static and dynamic tests of this glove use only a single IMU on one finger, which fails to meet real-world requirements for simultaneous measurement using multiple IMUs on an integrated glove [49]. Moreover, this glove presents opportunities for improvement: the design presents inconvenience in terms of disassembly and a more automated magnetometer calibration could be added to the system [43].

In a separate study by Fei Fei et al. [50], a modular data glove with twelve nine-axis Inertial and Magnetic Measurement Unit (IMMU) was designed for hand kinematics assessment, seen in Figure 2.3. It captures hand movement data through sensor units, which are then processed by a Microcontroller Unit (MCU) and transmitted to a computer via USB or Bluetooth.

Figure 2.3: Prototype of the proposed glove [50]

While accelerometer and gyroscope calibration parameters remain stable, the magnetometer requires periodic recalibration due to environmental influences. Consequently, multi-sensor fusion algorithms integrate acceleration, angular velocity and geomagnetism data to estimate IMMU sensor attitudes. The accuracy of the glove was tested by comparison with a goniometer, which showed that the proposed data glove provides accurate and stable hand motion parameters, resulting in an average error rate below 2% and maximum deviation of approximately 1.4 degrees, making it suitable for medical applications. However, some problems regarding limitations in data sampling rate, potential reliability issues with Bluetooth transmission and inconvenience in disassembly due to its modular design still remain [50].

Saggio et al. [46] proposed a testing procedure based on the assessment of dynamic measures to evaluate the performance of two of the most frequently used types of sensory gloves, one equipped with resistive flex sensors (RFS) and another with IMUs, both subjected to a series of dynamic tests. The IMU-based glove consisted of 18 nine-axis IMUs, strategically placed across the fingers and hand. The research focused on assessing the repeatability of these gloves in measuring finger joint angles, using a 3D-printed cone fixed on a table to ensure a consistent opening and movement throughout the test. Results found that while the RFS-based glove demonstrated slightly higher repeatability with an average range of 6.84 degrees ±2.77 degrees, the IMU-based glove still performed well, with a range of 8.49 degrees ±2.72 degrees.

Other recent literature compares both commercial and non-commercial glove-based systems, exploring various sensor technologies used in smart glove development for different purposes, as detailed in Tables I.1 and I.2. These gloves find application in virtual reality, robotics and increasingly in medicine, primarily for monitoring hand movements, though doubts persist about their medical accuracy. The evolution of data gloves, from early prototypes to advanced versions like the CyberGlove and Humanglove, is detailed, with current research focusing on enhancing accuracy and usability, particularly through IMU integration. Substrate materials are vital in smart glove design, with challenges in accommodating diverse hand shapes and sizes. In fact, materials must be durable, washable, flexible, lightweight and provide good skin adhesion for sensor accuracy. Exoskeleton designs offer an alternative approach, offering flexibility and unhindered wrist movement while integrating sensors along the exoskeleton body. Calibration is essential for accurate hand motion assessment but can be challenging, with factors like sensor non-linearity and user misalignment affecting accuracy, necessitating frequent calibrations for individual users [51].

2.1.2 Mechanical Data Gloves

Low-cost and simpler systems, such as mechanical data gloves, are also capable of monitoring ROM of the fingers. Othman et al. [52] designed and developed an adjustable angle sensor based on a rotary potentiometer, which operates by measuring the change in resistance due to the motion of the finger, allowing for the calculation of joint angles. The accuracy and reliability of the new sensor were assessed by comparing it with a flexible bend sensor, a standard tool used in finger flexion research. This comparison involved measuring finger bending angles at 10, 30 and 50 degrees using both sensors to evaluate their performance. The results demonstrated that the new sensor outperforms the flexible bend sensor in terms of accuracy and stability. Unlike the flexible bend sensor, which showed inaccuracies such as negative angles at 0 degrees and unreliable readings at 90 degrees, the new sensor provided consistent and stable measurements. Additionally, the new sensor exhibited high linearity of 99.89% and a repeatability error of less than 0.05. The findings demonstrate that such a system effectively measures finger flexion angles in real-time, providing stable output, being reliable, accurate and more suitable for clinical evaluation and hand rehabilitation when compared to popular flex sensors.

Tao Bai et al. [53] proposed a similar system with a different architecture, which includes connecting rods, sliders, potentiometers, springs and a signal processor, as seen in Figure 2.4. The glove fits on the back of the hand, with each finger placed in a designated sleeve. As the fingers bend, the connected rods move within a guide slot, altering the resistance of the potentiometer. The signal processing module then interprets the change in resistance, corresponding to the finger's bending degree, by measuring the output voltage of the potentiometers. However, this system's performance was not evaluated in the study.

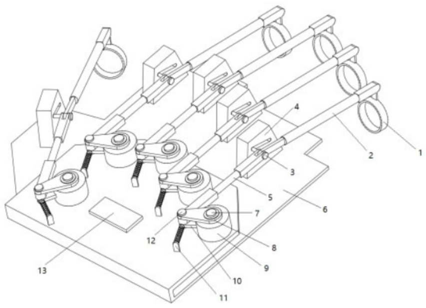
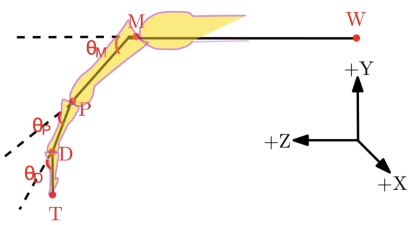


Figure 2.4: Prototype of the proposed mechanical glove [53]

2.1.3 Infra-Red Camera Systems for Range of Motion Assessment

In recent years, IR systems have gained prominence in the field of ROM assessment. These systems typically employ IR cameras, which operate on the principle of capturing IR radiation emitted by objects within their field of view. When a joint moves, the temperature distribution on the skin changes due to blood flow and muscle activity. Therefore, the camera's sensor captures this radiation and converts it into stereo images that can be further analyzed. With the use of a proprietary algorithm, these systems can precisely track the position of objects in 3D space with stereo vision, a method based on triangulation capable of finding the coordinates of a point in space based on its projections onto two or more images. Having these coordinates, the angles of the joints are easily calculated from the formulas in Figure 2.5 [44].



$$\theta_M = \cos^{-1}\left(\frac{\overrightarrow{WM} \cdot \overrightarrow{MP}}{\|\overrightarrow{WM}\| \cdot \|\overrightarrow{MP}\|}\right)$$

$$\theta_P = \cos^{-1}\left(\frac{\overrightarrow{MP} \cdot \overrightarrow{PD}}{\|\overrightarrow{MP}\| \cdot \|\overrightarrow{PD}\|}\right)$$

$$\theta_D = \cos^{-1}\left(\frac{\overrightarrow{PD} \cdot \overrightarrow{DT}}{\|\overrightarrow{PD}\| \cdot \|\overrightarrow{DT}\|}\right)$$

Figure 2.5: Calculation of the joints' angles [44]

Comparing with traditional methods, IR systems offer several advantages, enabling contactless measurement, eliminating the need for physical attachments, leading to a more comfortable and easier assessment of the patient. Secondly, these cameras provide precise measurements of joint angles with minimal error, ensuring accuracy and reliability in ROM assessment.

Gonçalves et al. [54] conducted an experimental validation of the Leap Motion Controller (LMC), a device featuring two cameras and three IR light emitting diodes (LEDs) that enables virtual interactions through hand gestures by capturing data on hand position and movement. The LMC was fixed on a table facing an industrial robot, which moved a wooden hand model in various orientations within the sensor's workspace. The hand model was tested in three configurations: open, fingers bent at 90 degrees and closed and angular displacements were measured along the lateral, vertical and frontal axes to examine its accuracy and repeatability in capturing hand movements.

The results suggest that the LMC is a promising, low-cost tool for continuous tracking of the wrist's ROM and could be effectively integrated into serious games for rehabilitation purposes. Its repeatability was notably high and it was able to accurately measure wrist movements with minimal errors. However, it displayed considerable errors in flexion measurements when the fingers were folded. Also, the study highlighted some other limitations, including the potential impact of reflective surfaces and lighting conditions on data uniformity.

Another exemplary application of IR technology in ROM assessment is the Ultra Leap hand tracking system. Ganguly et al. [44] compared this instrument with a marker-based motion capture system, focusing on finger kinematics. Results showed discrepancies in measuring finger joint positions and had low agreement with the gold-standard system, Qualisys Track Manager (QTM). In fact, the use of markers ensures a higher resolution, although having the problem of being more expensive and needing more preparation time. The study showed that the LMC was not suitable yet as a replacement for clinical settings, due to inconsistencies in dynamic tracking. Furthermore, it had a good performance in static conditions but struggled with dynamic tracking, especially for the ring and little fingers.

All these findings highlight both the potential and limitations of the LMC in rehabilitation therapy. While the LMC shows promise as a cost-effective tool for wrist rehabilitation, further research is needed to address its limitations, improve reliability in dynamic tracking and validate its performance in clinical settings. The ongoing development efforts by the LMC's development team, focusing on software and tracking algorithm improvements, suggest potential as a low-cost replacement for clinical evaluation tools, pending further validation and refinement.

3

Materials and Methods

The research work described in this dissertation was carried out in accordance with the norms established in the ethics code of Universidade Nova de Lisboa. The work described and the material presented in this dissertation, with the exceptions clearly indicated, constitute original work carried out by the author.

3.1 Materials

3.1.1 The Goniometer

For the inter-rater reliability test in this study, a small-arm goniometer, outlined in Figure 1.3, was employed by the physiotherapists to measure the participants' joint angles. The units of measurement of the goniometer are in degrees, with a resolution of two-degree increments. This instrument, routinely used in the clinic, is considered the gold standard for assessing the ROM of patients, having an accuracy of five degrees, as consistently supported by research in the literature [26].

3.1.2 Hand models

To ensure reliable measurements across different instruments, several hand models in various positions were created. This approach aimed to maintain consistent coordinates and angle values when using multiple ROM measurement instruments. The following materials were used for the silicone models: molding alginate (Michelangelo) and silicone (datasheet for specifications [55]).

To prepare the silicone model (Figure 3.1), the alginate mixture was first made by combining 450 grams of alginate with 1.8 liters of water to achieve the desired consistency. A volunteer's hand was then immersed in this mixture for approximately four minutes to form the necessary hand mold. Subsequently, the silicone mixture was poured into the alginate mold. The mold was then placed in a vacuum chamber, which facilitated the removal of air bubbles, ensuring a more uniform finish to the model. Once dry, the silicone model was carefully extracted from the alginate mold.

Figure 3.1: Illustration of the steps involved in creating the silicone hand model

The same procedure was replicated using plaster instead of silicone. However, despite the plaster's ability to capture finer details, the silicone was selected for the final models due to its superior durability, which makes it less prone to damage and more suitable for repeated use. Additionally, silicone offers greater ease of use, as its flexibility and resistance to movement facilitates easier handling and wearing of the glove. While silicone models may capture slightly less fine detail compared to plaster, the level of detail achieved is still sufficient for the purposes of ROM measurements.

3.1.3 Nuada Sensor Glove

The Nuada glove (prototype, NUADA, Porto, Portugal), represented in Figure 3.3, was developed by the Portuguese startup Nuada with the aim of facilitating the measurement of hand mobility. Its functionality can be summarized as follows: the device incorporates 18 nine-axis-IMU sensors BNO055 strategically positioned on crucial hand and wrist structures: one sensor for each phalanx of the five fingers, two on the hand and one on the wrist. Each sensor is equipped with an accelerometer, magnetometer and gyroscope. Furthermore, these IMUs employ a proprietary sensor fusion algorithm, delivering information in a quaternion form. To calculate the angle of a joint, both the sensor before the joint in question and the sensor after the same joint are considered. This means that, to determine the angle of the Proximal Interphalangeal (PIP) joint in Figure 3.2, both the sensor number three and sensor number four are used, as well as for the calculation of the angle of the Distal Interphalangeal (DIP) joint of the same finger, both the sensor number four and the sensor number five are required. It is crucial to note that the malfunctioning of one sensor can compromise the accuracy of the measurements for the other.

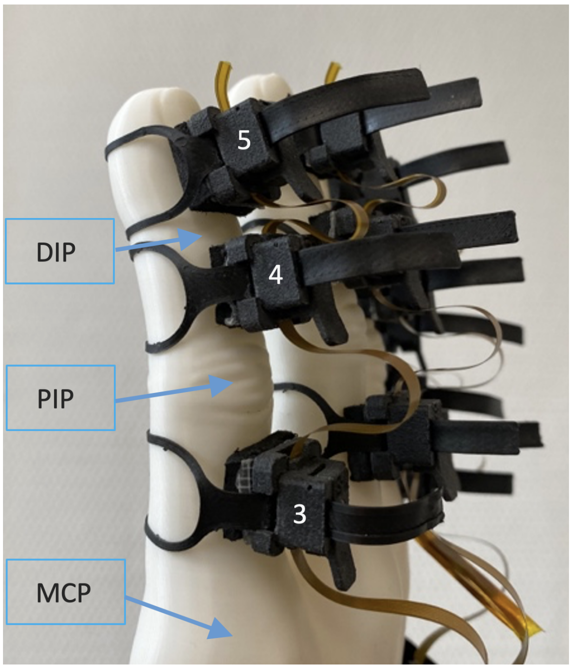


Figure 3.2: Position of the IMUs of the Nuada glove

In contrast to a typical textile glove, it adopts a ring-based system. This unique design enhances sensor attachment to specific phalanges, reducing errors significantly. Additionally, this ring-based structure facilitates easier wearability, especially for individuals with hand limitations compared to traditional textile gloves, designed to fit custom hand sizes by adjusting the rings.

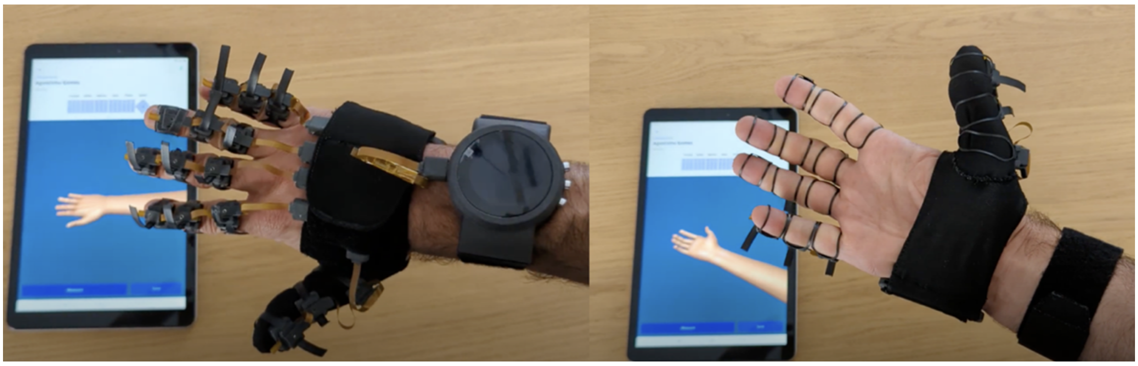


Figure 3.3: Nuada sensor glove prototype

The system's modularity is manifested through five flexes, one for each finger, each embedded with three sensors. These flexes connect to a palm-mounted board via Universal Serial Bus Type-C (USB-C) and this board further links to the wrist unit, also through USB-C. The wrist unit functions as a hub, collecting data from the 18 sensors and transmitting it via Bluetooth to a mobile application at a rate of 50 Hz, utilizing a highly optimized protocol. To start using the glove, a hard calibration is required to align the accelerometer, gyroscope and magnetometer. This involves positioning the accelerometer in six to eight fixed orientations, keeping the glove static for the gyroscope, and performing an eight-shaped movement for the magnetometer. Once this hard calibration is complete, only the magnetometer requires recalibration each time the system is restarted, necessitating the eight-shaped movement before starting measurements. This is a critical step because the magnetometers in the IMUs are highly susceptible to disturbances from environmental magnetic fields [56]. Through the Android application "Goniometry", users can check the calibration status of each sensor and identify any malfunctioning sensors. Each sensor has an associated square with a specific number and it needs to be green for it to be well calibrated, as seen in the picture 3.4. It should be noted that sensor 17 will always display red, as it has been disconnected by the developers due to malfunction. This calibration process results in the recreation of a highly precise 3D model of the hand, animated in real-time.

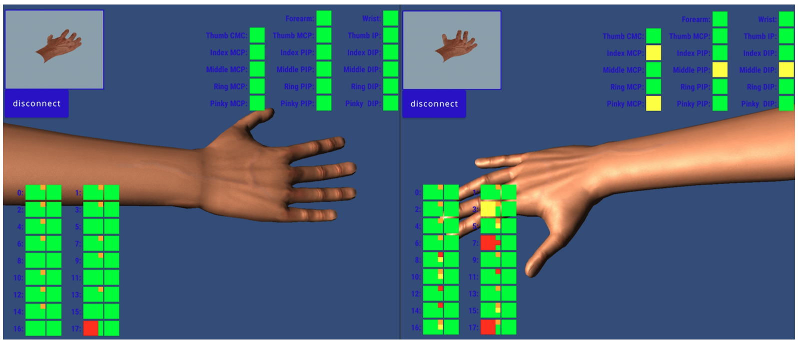


Figure 3.4: a) good calibration b) sensor 17 is not well-calibrated

After calibration, a "Tare" process is required, which sets all joint angles to zero degrees when the hand is placed flat on a table. This process aims to correct any errors from the calibration and sensor positioning. Currently, the mobile application is exclusive to the Android platform. The most recent version offers two possible modes: digital goniometry mode for measuring joint range of motions, analyzing all joint angles simultaneously by opening and closing the hand and a therapy mode, with a catalog of ten customizable exercises. In this study, only the goniometry mode was used, where the system records each patient's flexion and extension values for each joint, allowing a faster digital documentation. This enables a comparative analysis to determine whether there is an improvement in hand function based on the success of the physiotherapy.

3.1.4 UltraLeap Motion

The Ultra Leap system (UltraLeap hand tracking, Ultraleap, Bristol, England) features two 640x240-pixel near-IR cameras and three LEDs, has a range between 60 cm to 80 cm, a field of view of 140 degrees (horizontal) x 120 degrees (vertical) and can be used in different orientations [57], the desktop mode facing up from the table, Head-Mounted (HMD) mode, fastened to a virtual reality (VR) headset or screen top mode. The modes vary in the camera's positioning, so choosing the correct mode based on the camera's placement is essential for an accurate performance. By stereo vision images, a proprietary algorithm performs the calculation to obtain the position of the joints, being able to accurately measure the angles and track hand gestures with high precision. To access the joints' angles, we developed a software solution in collaboration with the Deutsche Forschungszentrum für Künstliche Intelligenz (DFKI) in Lübeck. This software, built using the UltraLeap Motion's technology, enables the recording of angles in degrees and saves the data in a CSV file, being its interface shown in Figure 3.5 b).

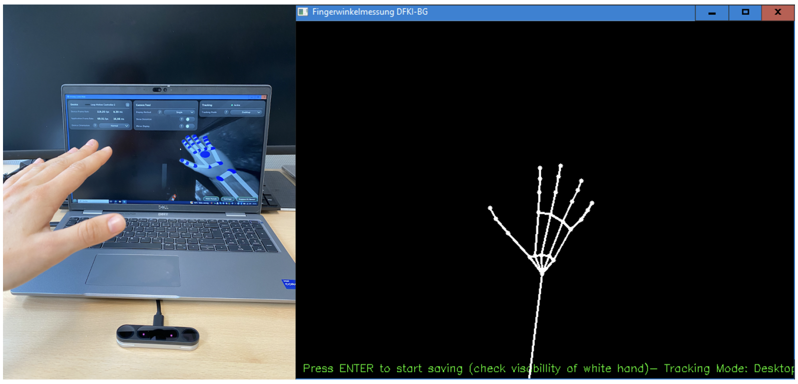


Figure 3.5: a) UltraLeap Motion software; b) Interface DFKI software

The software has the following keys: ENTER to start and stop the sequence saving; x to exit the software; h to select HMD tracking mode; s for the ScreenTop tracking mode and d for the Desktop mode. After a recording is completed, a CSV file is saved for analysis. Each column in the file corresponds to a specific joint, containing its angle values over time. There is also a "hand ID" column that indicates which hand was analyzed. This is useful in scenarios where two hands are being recorded simultaneously or if the system loses track of a hand during the recording but then re-recognizes it after a few seconds. In such cases, two different hand IDs will appear in the file.

3.1.5 Potentiometer data glove

Another instrument used in this study was a potentiometer-based glove, presented in Figure 3.6. In contrast to the Nuada glove, it utilizes the movement of fingers to modulate the resistance of rotational potentiometers, thereby enabling precise calculations of joint angles.

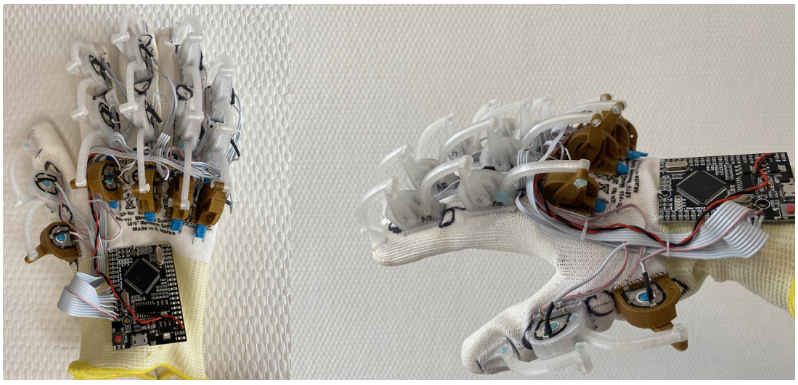


Figure 3.6: DFKI glove

In fact, the movement of the potentiometer's mechanical shaft changes the electrical resistance between the central terminal and the two outer terminals [58]. This change in resistance is then translated into calculations of the joint angles. When the glove is worn and the wearer moves their fingers, the resistance of the potentiometer varies caused by the bending of the shaft. This information is then processed to determine the joints' angles and the movements performed. The glove has 14 rotational potentiometers, three in each finger, except for the thumb which has two. All sensors are connected to a microcontroller in the back of the hand, the dorsal aspect.

3.2 Methodology

The methodology used in this dissertation can be divided into three groups. The first one is related to studying the inter-rater reliability of the gold standard instrument used in physiotherapy, the goniometer. The second refers to the repeatability of the alternative measuring instruments and the later constitutes the accuracy tests. In the following, the groups are explained in detail, before presenting the results in Chapter 4.

3.2.1 Inter-rater reliability

In order to show the need of a change in the way of how patient's ROM is being assessed, the research approach started with the study of the inter-rater reliability of physiotherapists when using the goniometer to assess hand joint mobility. The protocol involved five participants, four female and one male, with movement restrictions due to several causes, such as distal radius fracture with ulnar styloid avulsion, Scapholunate Ligament (SL) ligament lesions, open fractures, partial SL and Scapholunate Scapholunate Triquetral Ligament (SLT) ligament ruptures and persistent exercise-induced insufficiency after Triangular Fibrocartilage Complex (TFCC) lesions. All participants are admitted to the complex stationary rehabilitation hand department. Additionally, five therapists, each with a minimum of ten years of experience in hand physiotherapy, were involved in the study. Following a standardized protocol, approved by the ethic commission from the University of Lübeck (2024-428), the flexion and extension positions of all finger joints were measured using a small-arm goniometer for finger joints, a long-arm goniometer for wrist movements and a finger ruler for assessing fingernail palm distance (FPD) and fingernail table distance (FNTD), seen in Figure 3.7. However, for this study, only the measurements of all five fingers' joints using the small-arm goniometer were considered. Uniformity in measurement tools was maintained throughout the study by consistently using these specific instruments for each type of measurement. Additionally, a brochure detailing the warm-up movements and a form for therapists to record measurement values (with one form per therapist per table) were also used. During setup, the subjects were arranged in a circle with individual tables, while therapists, positioned outside the circle, rotated clockwise after measuring each one. Prior to measurements, participants performed a standardized warm-up, as outlined in the patient brochure, supervised by therapists. Subsequently, each therapist measured the AROM of all joints of the right hand once per participant, documenting results confidentially. Participant and therapist identities were coded to ensure anonymity, overseen by an independent supervisor. Inter-rater reliability was assessed using the ICC, categorizing the values to indicate the degree of agreement among therapists.

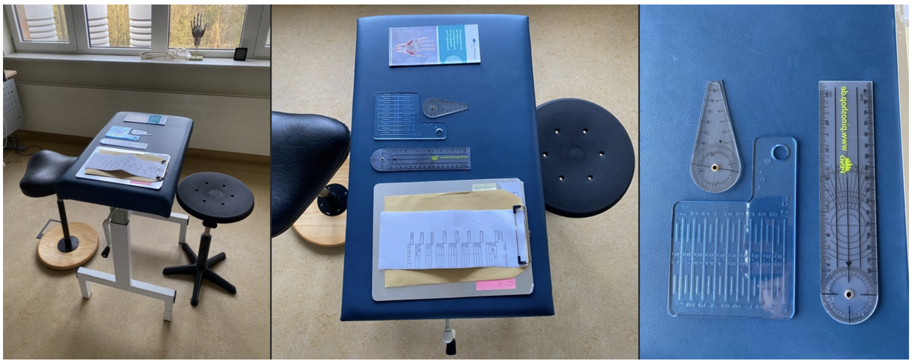


Figure 3.7: Instruments and Setup of the Inter-rater reliability test

3.2.2 Repeatability of measurement instruments

To assess the repeatability of the Nuada sensor glove, the mechanical glove and the UltraLeap Motion, the flat hand model was used and all the measurements were done in the same location under the same conditions, ensuring consistency among all instruments. All the calculations were done for all joints of each finger, unless it was not possible according to the instrument. Repeatability was calculated by determining the overall standard deviation, which involved following a specific calculation procedure for each measurement instrument to ensure consistency in the results.

3.2.2.1 Nuada sensor glove

The data acquisition process began with the Nuada sensor glove, testing the repeatability of its readings under various procedures: rotating the hand model in different directions, powering the watch on and off and removing and re-wearing the glove between trials. The first procedure aimed to evaluate the glove's performance by repeating the same rotation process multiple times consecutively, without any recalibration or repositioning of the sensors in between, ensuring no interference from the system. In contrast, the second and third procedures assessed the impact of system errors: the second focused on calibration errors, while the third examined the effect of sensor positioning errors. Ultimately, the variations in the overall standard deviation were observed to analyze the impact across all procedures. It should be noted that, the component to tighten the thumb's distal phalanx (DP) sensor is broken, causing the movement of the sensor and affecting the IP joint angle measurements. As a result, this sensor was excluded from the beginning.

Different Orientations:

The glove was placed on the hand model, the watch was turned on and the calibration process was performed. It was noted that the middle phalanx (MP) sensor of the middle finger was not properly calibrated, remaining red throughout the calibration process. This issue resulted in the exclusion of the middle finger for further analysis, as this sensor's malfunction also influenced the DP sensor. After assuring everything was ready, the hand model was then positioned on top of the laboratory's desk without any movement. The experiment involved rotating the hand model 90 degrees to four different orientations: North (N), West (W), South (S) and East (E), with the hand held in each direction for five seconds. Six rotations (trials) were made in total, having a graph shown in Figure 3.8 for each joint of each finger. Each rotation represents one trial and is separated by a vertical line. In each trial, the four different directions are represented with the four corresponding plateaus. In order to have a single value representing each direction, an average of these five seconds plateaus was calculated, seen in Table I.3. Finally, the overall standard deviation was computed using the average of the four directions data points.

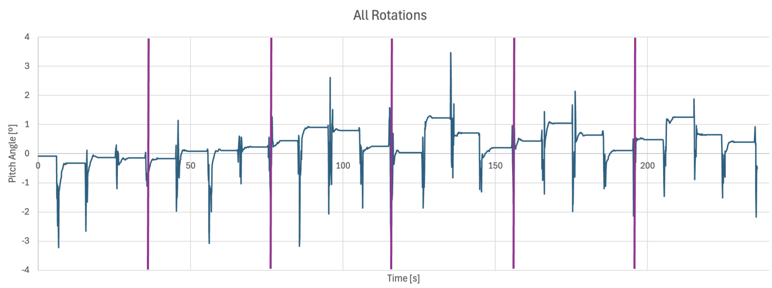


Figure 3.8: Graph of the index MCP angles during the six rotations

Watch Power On/Off:

In this experiment, five trials were conducted, with the watch component of the Nuada glove being powered off and back on between each trial, necessitating recalibration each time the watch was restarted. Each trial followed a consistent procedure: after calibration, the hand model was placed on the same desk in a specific position and a recording was started. The sequence involved the hand model remaining static for ten seconds, then being moved randomly for ten seconds, followed by another ten seconds of remaining static in the original position. This sequence was repeated six times per trial and the recording was stopped. Each trial produced a graph, presented in Figure 3.9, where the positive and negative peaks in the graph correspond to the dynamic phase and the plateaus correspond to the periods when the hand model was stationary on the desk. These plateaus provided the critical values for analysis, as they were averaged to produce a single representative value for each plateau, resulting in six data points per trial, represented in Table I.4. Consequently, the mean of the six averaged plateau values per trial was calculated to provide a single average value and the standard deviation was then computed using these five average values (one from each trial) for each joint. This approach demonstrated the repeatability of equal procedures, highlighting the glove's ability to consistently reproduce the same values when the system is re-calibrated.

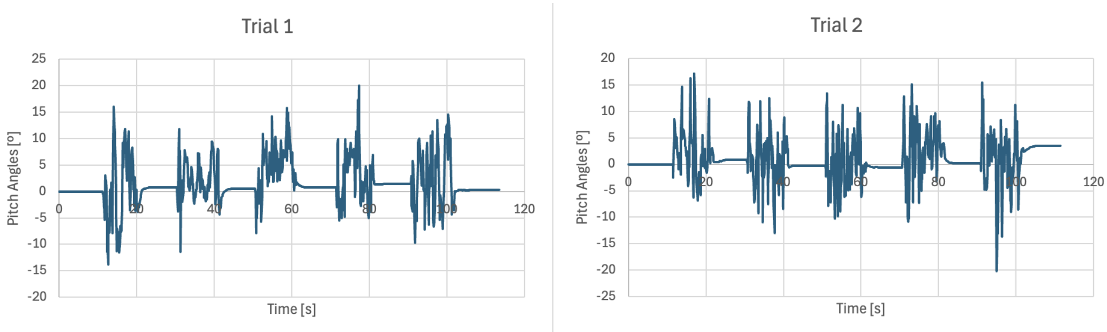


Figure 3.9: Graphs of two trials of the index MCP angles

Glove On/Off

Lastly, a similar procedure as described above was conducted. However, in this case, between trials, the glove was removed from the hand model and then placed back on. This approach demonstrated the glove's ability to consistently reproduce the same values when its position is varied by re-wearing the glove and performing a new calibration process.

Finally, a diagram, presented in Section 4.1, was created to compare the overall standard deviation values from the three processes: single calibration with varying directions, re-calibration and re-wearing with calibration to determine the influence of each factor on the repeatability of the measurements.

3.2.2.2 Mechanical glove

To evaluate the repeatability of the mechanical glove, we followed a similar procedure involving the following steps: the glove was initially placed on the hand model in a consistent static position and a measurement was taken. Following this, the fingers were moved to influence the mechanical rods of the potentiometers, simulating realistic usage conditions. After these movements, the hand model was returned to the original static position and another measurement was taken. This sequence of static measurement, finger movement and return to static measurement was repeated six times within each trial. In total, five trials have been conducted with the glove being removed and put back on the hand in between trials.

For each trial, the average of the six static position measurements was calculated, resulting in five average values corresponding to the five trials, being an example of the index MCP values represented in Table I.5. To assess the overall variability of the glove's measurements, the overall standard deviation of these average values was calculated. Given that the mechanical glove is potentiometer-based and not dependent on the position in 3D space, the random finger movements between static measurements were necessary to vary the joint angles. Additionally, using the hand model made it impossible to insert the thumb into the glove, making the thumb values unavailable for comparison.

By analyzing the overall standard deviation, the variability introduced by the glove's reapplication was investigated.

3.2.2.3 UltraLeap Motion

To evaluate repeatability of the UltraLeap Motion system, a different procedure was chosen due to the software's capability of only recording continuous measurements. Also, due to the difficulty of the camera system recognizing the hand model, primarily because of its lack of heat transmission, each measurement had to be conducted separately. More Specifically, by moving the hand while recording, significant time was often required for the camera to recognize it again after losing it. Therefore, after assuring the recognition of the hand model, it was placed on the table, static and always in the same position for 90 seconds. When stopping the recording, the hand model was moved randomly and then placed back on the desk for another recording. This sequence was repeated five times, being two of the total sequences represented in Figure 3.10

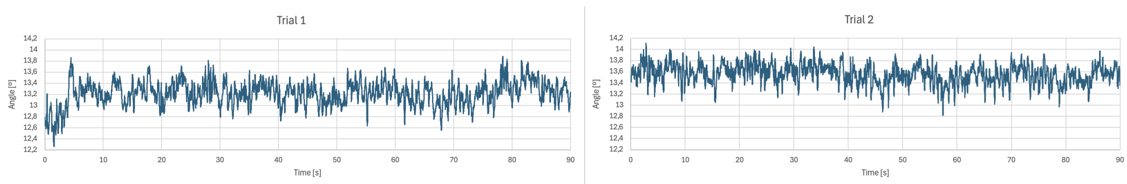


Figure 3.10: Graphs of two trials of the index MCP angles

For each of the five trials, the average of the recorded data points was calculated, resulting in five average values, represented in Table I.6. Like the approach used for the Nuada glove, the overall standard deviation for each joint using the camera was calculated with the average values from each trial. It must be noted that the software was programmed to set the thumb CM joint value at 180 degrees due to its difficulty of calculation, resulting in an overall standard deviation of zero. For this reason, the thumb CM angle value was not used for comparison, as it does not represent an actual measurement.

To compare the repeatability of the three instruments, the glove on/off procedure of the Nuada glove was chosen because it closely matched the procedures used for the other two instruments. For the mechanical glove, this involved moving the fingers randomly within each trial and re-wearing the glove between trials. For the UltraLeap Motion system, which does not use a physical glove, we replicated the re-wearing process by moving the hand model between recordings.

A bar plot was created (see Figure 4.2) to display the overall standard deviation values for each joint, enabling a clear comparison of repeatability across all three instruments. Due to the constraints of each device, the thumb and middle finger were not considered for comparison, for the reasons mentioned above.

3.2.2.4 Statistical tests

To conduct a detailed statistical analysis on the repeatability of the Nuada glove, a Friedman's test and the Wilcoxon test were employed. The Friedman's test was used to evaluate whether there are statistically significant differences not only between trials, but also within each trial. Specifically, this non-parametric test was applied in the following ways:

Between Trials: this test was used to rank the measured values from the same joint across different trials. This analysis determined if there were any significant variations when performing equal rotations consecutively, turning the watch on and off between trials and re-wearing the glove between trials.

Within Each Trial: For each trial, the test compared the differences observed within that trial to those across all five trials. Specifically, it compared the four orientations (North, West, South, East) within each trial for the first procedure and the six plateaus within each trial for the other two procedures.

The Wilcoxon test was employed to study the differences between the Nuada glove and the UltraLeap Motion system. This non-parametric test compared the paired measurements from both devices to determine if there were significant differences in their readings. The mechanical glove was excluded from this comparison due to its poor performance and high variability.

3.2.3 Accuracy of measurement instruments

To assess the accuracy of the measuring instruments, a comparison was made to determine how closely their results aligned with those obtained using the gold standard, the goniometer. For this comparison, one healthy volunteer was chosen, having no hand movement constraints.

Initially, an experienced hand physiotherapist measured four times the volunteer's flexion and extension angles of all joints using the goniometer. Following this, the same hand joints' flexion and extension angles were measured using the Nuada glove and the UltraLeap Motion camera system. Due to the design of the Nuada glove, it was not possible to measure with the goniometer while the glove was on, so separate processes were performed. The mechanical glove was excluded from this accuracy assessment because, during the repeatability tests, it was observed that its performance was inconsistent, with an average standard deviation higher than the accuracy of the goniometer. Therefore, it would not offer any advantage over the gold standard (see Section 4.2 for details). For the Nuada glove, the glove was put on and a calibration was performed. It must be noted that the MP sensor of the middle finger remained red, which also resulted in the exclusion of the middle finger from the comparisons. Also, due to repeatability results (see Figure 4.1), the thumb was excluded aswell. Flexion and extension measurements were performed four times each.

For the UltraLeap Motion camera system, the same hand joints were measured with the difference that each of the four values of extension and flexion were derived from the average of data recorded over ten seconds in extension and ten seconds in flexion. This was necessary due to the system's capability of only recording continuous measurements rather than discrete ones.

With four values of flexion and extension for each finger joint from each instrument, the differences and averages between the values were computed in order to construct Bland-Altman plots to compare each instrument's measurement values against those from the goniometer. These plots allow a visual comparison of how closely each instrument's measurements matched the goniometer's values, enabling the determination of which instrument showed better accuracy. The values of the Nuada glove were also compared with the UltraLeap ones, to visualize how close the values were from each other in order to take more conclusions about the goniometer.

3.2.4 Usability Analysis

A usability analysis was conducted for the three instruments to highlight various aspects of each, including ease of use, user comfort, interface and feedback and durability and maintenance, focusing on the following aspects:

- Ease of Use: The analysis assessed the simplicity and time required to set up and calibrate each instrument before use.

- User Comfort: The materials used in the instrument's construction were analyzed for their impact on comfort and how well the glove fits various hand sizes and shapes.

- Interface and Feedback: The usability of the software or app used to display and interpret the instruments' data was analyzed, focusing on clarity and ease of navigation.

- Durability and Maintenance: The glove's durability under regular use was assessed, considering factors like sensor fragility and overall longevity.

4

Results

4.1 Inter-rater reliability

The primary objective of this analysis was to evaluate the consistency ROM measurements taken by different therapists using a goniometer. The table below presents the percentage of measurements categorized by their corresponding ICC values, while detailed ICC values for individual measurements are provided in Table I.7.

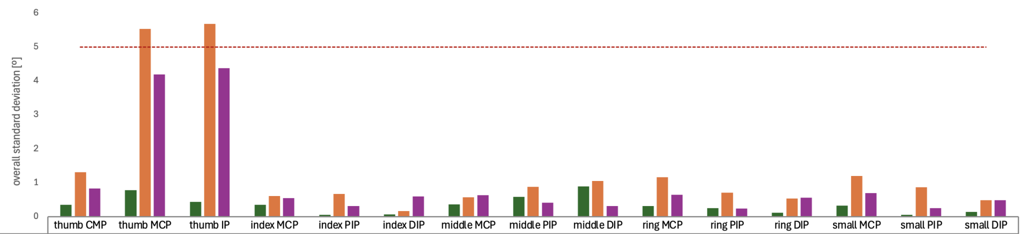
Table 4.1: Percentage of the measurements according to their ICC values

ICC values	Measurements [%]
ICC ≥ 0.9	0
0.75 ≤ ICC < 0.9	31.0
0.5 ≤ ICC < 0.75	24.1
ICC < 0.5	44.8

The analysis of ICC values in Table 4.1 reveals varying levels of agreement among raters using a goniometer. Notably, a substantial proportion (44.8%) of measurements have ICC values below 0.5, indicating poor agreement. Additionally, 24.1% of measurements fall within the moderate agreement range of 0.5 to 0.75, suggesting ongoing variability in outcomes. While 31% of the measurements indicate good agreement (ICC between 0.75 and 0.9), this percentage is relatively modest and there is a complete absence of measurements with excellent agreement (ICC ≥ 0.9). Also, from Figure I.1, it is evident that joint flexion consistently exhibits higher ICC values than joint extension.

4.2 Repeatability of measurement instruments

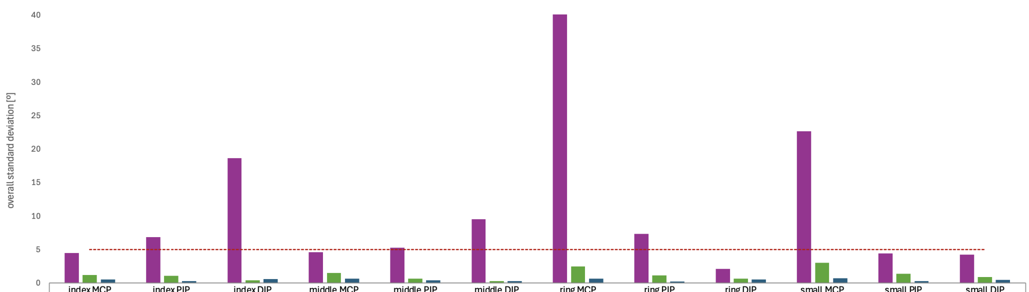
In Figure 4.1 the overall standard deviation for each finger joint across the three different experiments using the Nuada glove is displayed. To compare these results with the goniometer measurement accuracy, a horizontal red dotted line at five degrees was included. 43/45 values fall below this line, indicating that the majority of overall standard deviations are under five degrees. However, during the watch on/off and glove on/off experiments, the thumb MCP and thumb IP exhibit a standard deviation above five degrees, which was expected since the thumb sensors are not working properly.



	thumb CMP	thumb MCP	thumb IP	index MCP	index PIP	index DIP	middle MCP	middle PIP	middle DIP	ring MCP	ring PIP	ring DIP	small MCP	small PIP	small DIP
Different Orientations	0.35	0.79	0.44	0.35	0.06	0.07	0.37	0.59	0.9	0.32	0.25	0.12	0.33	0.06	0.14
Watch On/Off	1.31	5.54	5.68	0.61	0.67	0.17	0.57	0.88	1.06	1.17	0.71	0.54	1.2	0.87	0.49
Glove On/Off	0.83	4.19	4.38	0.55	0.32	0.6	0.64	0.41	0.32	0.644	0.24	0.56	0.7	0.26	0.49
Goniometer Accuracy															

Figure 4.1: Overall standard deviation of each joint across the different procedures conducted with the Nuada glove

To compare the values of the three instruments, the standard deviation values of the glove on/out experiment with the Nuada glove was compared with the overall standard deviation of the experiments conducted with the UltraLeap and the mechanical glove. In Figure 4.2, one can see that the mechanical glove has high standard deviation values comparing to the others, having a high variability for repeated methods. For this reason, this instrument was excluded from further analysis, as it was determined not to be a reliable measuring tool.



	index MCP	index PIP	index DIP	middle MCP	middle PIP	middle DIP	ring MCP	ring PIP	ring DIP	small MCP	small PIP	small DIP
Mechanical Glove	4.47	6.83	18.66	4.6	5.3	9.52	43.64	7.32	2.14	22.65	4.45	4.21
UltraLeap Motion	1.23	1.05	0.4	1.52	0.67	0.31	2.5	1.16	0.64	3.05	1.38	0.9
Nuada's Glove	0.55	0.32	0.6	0.64	0.41	0.32	0.644	0.24	0.56	0.7	0.26	0.49
Goniometer´s Accuracy												

Figure 4.2: Overall standard deviation of each joint across the different measuring instruments

For a more detailed comparison, the standard deviation values of the mechanical glove were excluded, leaving only those of the UltraLeap and Nuada. It is evident that the standard deviations for all joints in both instruments are below five degrees, indicating very good repeatability. Notably, for all joints except the index DIP, the Nuada's values are smaller than those of the UltraLeap, demonstrating higher repeatability.

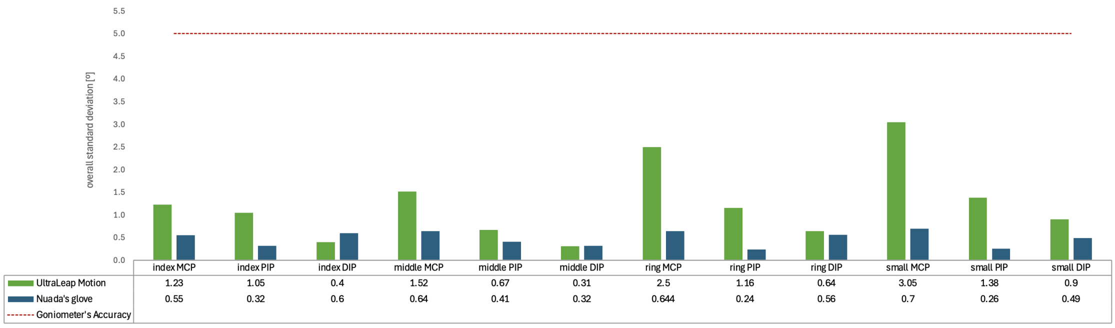


Figure 4.3: Overall standard deviation for each joint across the remaining measuring instruments

4.2.1 Statistical tests

In both Tables 4.2 and 4.3, the p-values within and between trials are presented for each procedure using the Nuada glove as well as the standard deviation values. Table 4.2 shows a significant statistical differences within trials in several joints, highlighted in bold (p-value < 0.05). However, it is crucial to interpret these findings in the context of their clinical relevance. Despite the presence of numerous statistically significant differences in some joints, the overall standard deviation for these measurements remains very small. This indicates that, while the statistical tests detect differences, the magnitude of these differences is minimal. Consequently, these differences are considered clinically irrelevant. The consistency in measurements, despite statistical variability, demonstrates that the glove's performance is repeatable for all joints.

Table 4.2: Friedman's test results for Different Directions

		Different Orientations:		
		p-value		**standard deviation [°]**
		within trials	between trials	
index	MCP	0.172	**0.014**	0.45
	PIP	0.079	0.982	0.37
	DIP	**0.010**	0.377	0.25
ring	MCP	**0.001**	0.293	1.02
	PIP	**0.007**	0.678	0.67
	DIP	**0.035**	0.790	0.56
small	MCP	**0.000**	0.006	0.80
	PIP	**0.010**	0.738	0.33
	DIP	**0.004**	0.093	0.35

Table 4.3 shows no statistical differences within trials for both the watch on/off and glove on/off procedures. However, there are statistical differences between trials. The same justification applies here as above; the standard deviation remains very small, making these differences clinically irrelevant. Thus, despite the statistical significance, the

actual impact of these differences on clinical practice is minimal, affirming the reliability of the glove under different conditions.

Table 4.3: Friedman's test results for watch on/off and glove on/off

		Watch on/off:			Glove on/off:		
		p-value		**standard deviation [°]**	**p-value**		**standard deviation [°]**
		within trials	between trials		within trials	between trials	
index	MCP	0.537	0.126	0.95	0.199	0.082	0.81
	PIP	0.761	**0.027**	0.80	0.178	0.443	0.83
	DIP	0.796	0.736	0.46	0.521	0.294	1.00
ring	MCP	0.389	**0.004**	1.24	0.490	**0.050**	1.17
	PIP	0.416	**0.004**	0.78	0.977	0.582	0.65
	DIP	0.813	0.064	0.72	0.053	**0.045**	0.82
small	MCP	0.975	**0.002**	1.33	0.621	0.060	1.35
	PIP	0.402	**0.011**	1.00	0.303	0.294	0.67
	DIP	0.382	**0.004**	0.68	0.621	**0.031**	0.67

The Wilcoxon test results show statistical significance differences between the camera and glove methods for all joints. This is evident from the identical p-values across all joints (p-value = 0.0079), which results from having the same number of samples for each comparison and the test's reliance on the sum of ranks. Since these p-values are below the typical significance level of 0.05, it demonstrates that the measurements from the Nuada glove and the UltraLeap device differ significantly.

4.3 Accuracy of measurement instruments

Based on the BA plots shown in Figures I.2 to I.7, the following tables display the bias values and the intervals (calculated as the absolute difference between the upper and lower limits). Table 4.4 presents the comparison between the values from the Nuada glove and the goniometer, as well as the comparison between the UltraLeap and the goniometer. Table 4.5 compares the values from the Nuada glove with the UltraLeap ones. The lowest bias values were identified in bold to determine which instrument most closely matched the goniometer.

For the Nuada glove, several movements exhibited very low bias values, indicating a high degree of accuracy. Specifically, the MCP flexion and extension of the index finger showed bias values of 0.11 and -1.05 degrees, respectively. Additionally, the MCP flexion and PIP extension of the ring finger had bias values of 1.45 and 3.45 degrees, respectively, while the PIP extension, DIP flexion and extension of the small finger displayed bias values of 2.44, 1.14 and -2.14 degrees, respectively. These low bias values suggest that the average difference between the Nuada glove and the goniometer is minimal, demonstrating good accuracy for these specific movements. However, 11 out of 18 movements still exhibit a difference greater than five degrees, showing that these glove's measurements remain significantly different from those of the goniometer. Furthermore, more than half of the bias values were positive, indicating that the Nuada glove tends to overestimate the goniometer readings in ten out of 18 cases. In contrast, the UltraLeap device showed fewer movements with low bias values, with only three out of 18 measurements falling into this category. Only the MCP extension and DIP flexion of the index finger and the DIP extension of the small finger had low bias values, while the rest of the movements exhibited differences greater than five degrees. Regarding the intervals, Figures I.2 to I.7 illustrates that 95% of the data falls within the intervals most of the time. However, some movements have wider intervals than others, indicating variability in accuracy across different movements.

Table 4.4: Bland-Altman plot results. G(Goniometer) F(flexion) E(extension). Bold letters indicate the joints and movements for which the two measurement techniques reached a good agreement. The Bland-Altman plots for these joints are illustrated in Figures I.2 to I.7.

			Bias [°]		Interval [°]	
			Nuada/G	**UltraLeap/G**	**Nuada/G**	**UltraLeap/G**
index	MCP	F	**0.11**	-5.13	28.26	36.75
		E	**-1.05**	**-1.57**	13.71	20.10
	PIP	F	-9.41	-5.54	3.11	11.79
		E	8.94	13.78	21.85	14.36
	DIP	F	-16.61	**4.60**	15.31	53.39
		E	7.80	8.28	15.95	20.03
ring	MCP	F	**1.45**	18.92	32.48	12.84
		E	11.97	-6.84	10.64	15.61
	PIP	F	-7.47	-5.42	45.16	14.06
		E	**3.45**	11.74	10.43	14.65
	DIP	F	-12.43	24.85	41.80	18.60
		E	10.23	12.80	11.88	2.05
small	MCP	F	-13.67	20.18	24.11	8.50
		E	-9.21	-11.13	14.67	31.39
	PIP	F	7.45	9.88	53.15	31.94
		E	**2.44**	-9.13	10.85	8.20
	DIP	F	**1.14**	13.19	34.31	12.00
		E	**-2.14**	**-1.04**	15.11	11.67

To determine the validity of the differences between each instrument and the goniometer, a comparison was made between the values from the Nuada glove and UltraLeap device, represented in Figure 4.5. This comparison revealed lower differences across more joints compared to when each instrument was individually compared with the goniometer. Specifically, low bias values were observed for MCP extension, PIP flexion and DIP extension of the index finger; PIP flexion and DIP extension of the ring finger; and MCP flexion and extension, PIP flexion and DIP extension of the small finger. Only MCP extension and DIP extension show a low bias when comparing the Nuada glove with the UltraLeap and both instruments with the goniometer.

Table 4.5: Bland-Altman plot results for Nuada vs UltraLeap. F(flexion) E(extension). Bold letters indicate the joints and movements for which the two measurement techniques reached a good agreement. The Bland-Altman plots for these joints are illustrated in Figures I.8 to I.10

			Bias [°]	Interval [°]
index	MCP	F	5.24	15.9
		E	**0.53**	6.62
	PIP	F	**-3.86**	13.72
		E	-4.85	-8.92
	DIP	F	-21.21	65.67
		E	**-0.48**	5.36
ring	MCP	F	-17.47	40.66
		E	18.81	5.74
	PIP	F	**-2.05**	42.62
		E	-5.26	14.56
	DIP	F	-37.28	-31.09
		E	**-2.58**	12.29
small	MCP	F	-33.85	-25.89
		E	**1.93**	19.38
	PIP	F	**-2.43**	28.31
		E	11.57	8.51
	DIP	F	-12.05	-22.78
		E	**-1.08**	15.54

4.4 Usability Analysis

The usability analysis of the three measuring instruments was conducted to assess their practicality in clinical settings. This evaluation considered several critical aspects, including ease of use, user comfort, interface functionality and durability. The following table provides a comparative summary of the findings for each instrument, highlighting both their strengths and limitations.

Table 4.6: Usability Analysis of the measuring instruments

	Nuada sensor glove	UltraLeap	Mechanical Glove
Ease of Use	• Quick to put on (5 minutes) • Not dependent on the rater • Calibration affected by surroundings • Challenging for patients to perform eight-shape calibration • Cable-free operation	• No need for calibration • Fast camera setup • Requires USB-C cable • Not dependent on the rater	• Easy calibration • Requires USB-C cable • Not dependent on the rater • Time-consuming to put on for patients with movement limitations
User Comfort	• Ring-based system makes it easier to put on • Adjustable rings eliminate the need for different hand sizes • Very lightweight	• Contactless	• Normal textile glove • Fingers must fit perfectly in the glove
Interface	• Requires an Android tablet • Results displayed via an application	• Requires a Windows computer • Software is user-friendly • Does not recognize amputations	• Requires a Windows computer • Software is user-friendly
Durability and Maintenance	• Sensors are fragile and prone to damage	• Long-lasting durability	• Numerous wires may cause malfunctions

5

Discussion and Conclusions

The inter-rater reliability analysis revealed significant insights into the performance of the goniometer in measuring joint movements. Movements such as MCP flexion of all fingers (except MCP of the small finger) demonstrated high reliability (ICC > 0.75) while extension of all finger joints (except for PIP of the ring and finger) showed low reliability (ICC < 0.5). Notably, joint flexion consistently showed higher ICC values compared to extension. This discrepancy is likely due to the more challenging and less consistent placement of the goniometer during extension movements, as discussed by McGee et al. [59], who attributed this to visualization challenges of bony landmarks and joint impairments in participants with pathological constraints. Particularly, the reliability of DIP flexion and extension for all fingers was notably low, aligning with Lewis et al. [60], who found that measuring DIP joints is difficult due to the goniometer's shorter lever arms and manipulation challenges. However, the reliability in our study was even lower, due to participants having movement limitations, unlike the healthy adults in Lewis et al.'s study. The observed variances among raters were high, which aligns with expectations given the limitations of the goniometer and the nature of the patients assessed. Our study's small sample size likely contributed to less reliable ICC estimates. McGee et al. [59] emphasized the need for larger sample sizes to achieve sufficient statistical power, recommending at least 30 subjects for reliable ICC estimates. Therefore, future studies should aim to include this sufficient number of participants to improve reliability.

Moreover, our patient cohort consisted of individuals with varying degrees of hand movement restrictions, leading to variability in their ROM over time. Engstrand et al. [26] discussed how repeating the same motion several times could influence results due to learning, motivation, or fatigue, leading to systematic changes in the average results. The use of the goniometer, despite its widespread acceptance, introduces imprecision into measurements. Reissner et al. [10] found that a 3D motion capture system met the reliability criterion (ICC > 0.7) for 94% of joints compared to 65% with the goniometer, highlighting the goniometer's limitations in detecting smaller changes in joint mobility. Hancock et al. [61] further showed that the minimal significant differences for long-arm and short-arm goniometers are ten degrees and 14 degrees, respectively, underscoring their limitations in clinical settings. For these reasons, a change in the assessment method is needed to improve measurement consistency, which can be achieved with alternative measurement devices.

The repeatability analysis of the Nuada glove demonstrated promising results. Interestingly, while it was expected that the overall standard deviation would increase across different procedures due to cumulative errors as seen in the study of Saggio et al. [46], this pattern was not consistently observed. In certain cases, such as the index PIP and middle MCP joints, the standard deviation values of the glove on/off procedure are higher than the watch on/off one, however, for other joints, the standard deviations did not show this expected increase. This phenomenon can be attributed to the interaction of calibration and positioning errors. The calibration of the sensors can vary significantly based on the surrounding environment, such as the presence of numerous electronic devices or the deterioration of a sensor over time. Additionally, positioning errors occur due to variations in how the glove is worn and how the sensors are placed during measurements. The relationship between these errors can be complex. If both errors have the same directional bias (e.g., both tending to overestimate the angle), their effects are additive, leading to a larger cumulative error. Conversely, if the errors have opposite directional biases (e.g., one overestimates while the other underestimates), they can partially cancel each other out, resulting in a smaller net error. This explains why in some procedures, despite multiple sources of error, the overall standard deviation remains low or does not increase as expected. Additionally, the "Tare" process, conducted at the beginning, aims to correct all these errors by assuming a target position, where the hand is flat with all joints making a 180 degrees angle with the table. However, this assumed position is not always accurate, which can affect the effectiveness of the error correction.

The Friedman's test revealed that, although some statistical differences were present, they are not clinically relevant due to the very low standard deviation (below one degree) observed in the measurements. For the different orientations (North, West, South, East), significant differences were found within each direction, but no differences were observed between trials. This indicates that the Nuada glove demonstrates excellent repeatability when performing the same movement consecutively, without any changes between sequences.

Similarly, in the watch on/off and glove on/off tests, no significant differences were detected within trials, suggesting that random movements do not affect the accuracy of the measurements when returning to the same position. Although some differences were noted between trials, these can be attributed to recalibration and sensor repositioning. However, these differences are not clinically relevant, as the low standard deviations indicate that the measurements remain consistent across multiple trials.

Despite potential sources of error, the glove demonstrated very high repeatability across all the different procedures. This finding is consistent with the work of Bor-Shing Lin et al. [43], who validated the reliability and stability of an IMU-based data glove, highlighting its strong correlation and accuracy in both static and dynamic scenarios.

Their data glove exhibited a mean error of three degrees during motion, which is within an acceptable range for rehabilitation tasks and hand function assessments. Similarly, [46] conducted repeatability tests on IMU sensors, reporting standard deviations per joint ranging from 2.2 degrees to 3.7 degrees, indicating solid performance. Our results, though obtained through different methodologies, align with these studies, confirming that the Nuada glove achieves good repeatability, outperforming traditional measurement devices in reliability.

When comparing the repeatability of the Nuada glove with the other two instruments, it became clear that the mechanical glove did not have a good performance, as reflected by its high standard deviation values, which was attributed to issues such as malfunctioning of the connection wires between the potentiometers and the microcontroller. Additional tests revealed that this glove was not very sensitive to small angle changes, making it unsuitable for clinical purposes. For these reasons and with the primary focus on the Nuada glove, it was decided to exclude the mechanical glove from further analysis and instead focus on the camera system for comparison, which showed very good repeatability, with most overall standard deviation values below three degrees. These findings align with those of Gonçalves et al. [54], who evaluated the performance of the LMC using a wooden hand performing movements across the lateral, vertical and frontal axes with static finger positions. They concluded that such system is a viable option for tracking wrist rehabilitation, achieving a mean repeatability of 1.74 degrees in the transversal configuration, which was the adopted configuration in this study.

Additionally, they are also in concordance with those of [62], who focused on the segment lengths derived from the Euclidean distance of the joint centers of each phalange, concluding that for static tracking using a mannequin arm, the LMC showed high repeatability, with standard deviations below 0.5 mm.

Looking at the comparisons between the goniometer and the Nuada glove, few movements using the glove exhibited very low bias values, demonstrating good accuracy for these specific movements. However, eleven out of 18 movements still exhibit a difference greater than five degrees, indicating that the glove's measurements are significantly different from those of the goniometer. Furthermore, more than half of the bias values were positive, indicating that the Nuada glove tends to overestimate the goniometer readings in most cases. This differs from the Hazman et al. [47] findings, which showed low percentage of error when comparing goniometer values with an IMU-based glove, indicating high accuracy. They compared only the index finger's joints measurements, by flexing the finger and returning to the relax position. Also, our findings differ from the study by Fei Fei et al. [50], where the angles measured by the goniometer and the data glove had an average error rate of less than 2% and a maximum deviation of nearly 1.4 degrees, indicating a high level of accuracy. In our study, however, while the Nuada glove demonstrated good accuracy for some movements (with deviations below three degrees), the majority showed discrepancies exceeding five degrees when compared to goniometer measurements. These differences can be explained by the inability to simultaneously measure with both the goniometer and the glove due to the glove's design, which could have improved the accuracy results or provided a clearer comparison between instruments. Additionally, the differences may also be attributed to the fact that the goniometer measures joint angles individually, while the glove captures the angles of all joints simultaneously. Also, the method used to measure DIP and PIP ROM differs between the two tools: the goniometer measures these joints individually by bending them in isolation, while the Nuada glove captures the angles during a full fist motion. In total, these differences in measurement techniques individually contributed and summed up to the discrepancies observed in our results.

In contrast, the UltraLeap device showed minimal agreement with the goniometer, with only the index MCP extension and small DIP extension demonstrating low bias values. These findings align with [25], where a comparison between the Leap Motion system and the goniometer was made and results showed that most joints also revealed minimal agreement. The authors suggested that this discrepancy might be partially due to the goniometer assessing individual joint movements while the Leap system assesses all fingers together. They also noted that the goniometer measures the dorsal side with the center of rotation outside the joint, whereas the Leap Motion sensor estimates the center of rotation inside the joint. Additionally, the discrepancies may also arise from the internal limitations of the Leap Motion sensor, which relies not only on camera visualization but also on the accuracy of its internal hand model. It was also observed that the sensor tends to estimate, rather than accurately measure, joint angles during occlusion, which can be solved by using multiple Leap Motion sensors.

Lastly, when comparing the Nuada glove with the UltraLeap system, lower differences across more joints were found compared to when each instrument was individually compared with the goniometer. This observation suggests that the goniometer, while being the clinical standard, it may not be as reliable as these more advanced systems.

Summing up, this study investigated the performance and reliability of an IMU-based glove compared to traditional and advanced measurement instruments, including the goniometer and an IR camera system, in assessing hand mobility. While the Nuada sensor glove shows great potential to improve the efficiency and repeatability of hand mobility assessments in clinical settings, further developments are necessary to enhance its accuracy and ensure it can serve as a reliable alternative to traditional instruments. The IR camera system also showed strong performance, particularly in repeatability, making it a viable alternative for hand mobility assessment in clinical settings.

5.1 Limitations and Future Work

This work faced several limitations which impacted the study's scope and results. Firstly, I was unable to test the repeatability of joint movements dynamically and had to rely solely on static measurements using a static hand model. This limitation prevented a comprehensive assessment of joint repeatability under real-life conditions. Therefore, there is a need to validate dynamic angles by developing a system that can consistently bend the fingers at the same angles while wearing the glove, as demonstrated in [49].

Additionally, when measuring accuracy, I encountered difficulties in simultaneously using the glove and the goniometer, which may have introduced discrepancies in the data. Also, the calibration process for the Nuada glove was inconsistent, with some days delivering good results, while on others, certain sensors failed to calibrate correctly. As new sensors for the Nuada glove are currently under investigation, it would be interesting to compare their performance with the existing ones to assess potential improvements.

Regarding the UltraLeap, an attempt to include a participant with hand movement impairment revealed another challenge: the camera system could not accurately recognize the participant's fingers, as they struggled to separate them effectively. This issue highlighted the limitations of this device in handling cases involving severe movement constraints. For this reason, testing its software with more than one camera could help reduce occlusion issues and enhance overall accuracy, particularly in challenging scenarios like those involving impaired hand movement. Lastly, software improvements are needed to enable the camera to recognize amputations.

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I

Annex A. Additional Results

I.1 Commercial and non-commercial glove-based systems

Data Glove	Use	Sensors Type	Joints Monitored	Cost
Cyber Glove III 	Motion capture environment	22 Flex bend sensors	All MCP, PIP and DIP joints of fingers IP, MCP and CMC joints of thumb Splay of all digits, wrist and palm arch movement	$15,000
5DT Ultra 14 	Motion capture and animation	14 proprietary optical-fiber flex sensors	All MCP and PIP joints of fingers MCP and IP joints of thumb Splay of all digits	£5000
Neofect: Raphael 	Clinical	5 Flex bend 2 IMU	Fingers, wrist and forearm movement	$15,000
Manus: Prime II Xsens 	Character animation	10 flex bend 5 IMU	All MCP and PIP joints of fingers IP, MCP and CMC joints of thumb	$5000–$6000
StretchSense: MoCap Pro SuperSplay 	Film and game animation	6 Capacitive	All MCP and PIP joints of fingers MCP and IP joints of thumb Splay of all digits and wrist movement	$7150

Table I.1: Commercial Data Gloves

Data Glove	Use	Sensors Type	Joints Monitored	Not Monitored	Cost
Tyndall/UU:Version 2	Clinical	16 IMU (9 DOF)	All MCP, PIP and DIP joints of fingers CMC, MP and IP joints of thumb Splay of all digits	DIP of the fingers CMC of thumb	£26,000
Tyndall/UU:Version 3 VR 	Clinical/VR	12 IMU (9 DOF)	All MCP and PIP joints of fingers IP and MCP joints of thumb Splay of all fingers and wrist movement	DIP of fingers CMC of thumb	£12,000
ActionSense 	Clinical	5 Flex bend	All MCP and PIP joints of fingers IP and MCP joints of thumb	DIP joints of fingers CMC joint of thumb Abduction and adduction between fingers	£400
SensoriGlove 	Clinical	Flex sensors Force sensors	All MCP and PIP joints of fingers DIP joints of fingers	DIP joint of fingers	–

Table I.2: Research Data Gloves

I.2 Repeatability of the Nuada glove

I.2.1 Different Directions

Table I.3: For the index MCP joint: Average values of the five-second plateaus for each direction per trial, along with the mean of these averages and the overall standard deviation. All measurements are in degrees.

	trial 1	trial 2	trial 3	trial 4	trial 5	trial 6
plateau1 (N)	-0.09	-0.17	0.45	0.04	0.43	0.48
plateau2 (W)	-0.32	0.08	0.90	1.23	1.04	1.25
plateau3 (S)	-0.13	0.11	0.79	0.71	0.64	0.65
plateau4 (E)	-0.14	0.22	0.25	0.20	0.11	0.40
mean [°]	-0.17	0.06	0.60	0.55	0.56	0.70
overall std [°]	0.349					

I.2.2 Watch on/off

Table I.4: For the index MCP joint: Average values of the five-second plateaus for each direction per trial, along with the mean of these averages and the overall standard deviation. All measurements are in degrees.

	trial1	trial2	trial3	trial4	trial5
plateau1	-0.09	0	0	0.11	0
plateau2	0.72	2.09	2.27	0.10	0.34
plateau3	0.72	1.33	2.56	0.06	-0.22
plateau4	0.69	1.06	0.57	-0.52	-0.06
plateau5	0.54	0.99	1.60	-0.15	-0.21
plateau6	1.24	0.02	0.90	1.59	-0.20
mean [°]	0.637	0.915	1.317	0.198	-0.058
overall std [°]			0.55		

I.2.3 Mechanical glove

Table I.5: For the index MCP joint: Six static measurements per trial, along with the mean of these averages and the overall standard deviation. All measurements are in degrees.

	trial1	trial2	trial3	trial4	trial5
measurement1	180	180	180	180	180
measurement2	174	183	182	174	183
measurement3	157	183	186	169	138
measurement4	173	176	187	166	170
measurement5	178	178	176	180	170
measurement6	178	179	181	178	188
mean [°]	173.3	179.8	182.0	174.5	171.5
overall std [°]			4.47		

I.2.4 UltraLeap

Table I.6: For the index MCP joint: Average values per trial, along with the mean of these averages and the overall standard deviation. All measurements are in degrees.

	trial1	trial2	trial3	trial4	trial5
averages	5.95	5.49	5.69	2.65	5.55
mean [°]			5.06		
overall std [°]			1.36		

I.3 IRR results

Table I.7: ICC results for all finger joints. Abbreviations: F(Flexion) E(Extension) RA(Radial Abduction).

	Segment	Movement	ICC
thumb	MP	F	0.853
		E	0.239
	IP	F	0.763
		E	0.348
		RA	0.630
index	MCP	F	0.886
		E	0.445
	PIP	F	0.628
		E	0.109
	DIP	F	0.349
		E	0.000
middle	MCP	F	0.894
		E	0.340
	PIP	F	0.723
		E	0.361
	DIP	F	0.509
		E	0.063
ring	MCP	F	0.761
		E	0.299
	PIP	F	0.754
		E	0.617
	DIP	F	0.768
		E	0.109
small	MCP	F	0.539
		E	0.386
	PIP	F	0.763
		E	0.845
	DIP	F	0.538
		E	0.125

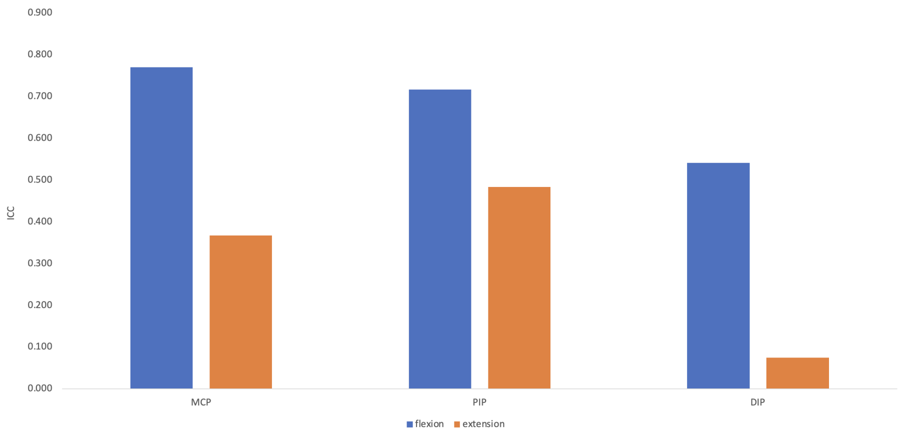

Figure I.1: Average ICC Values for Joint Flexion and Extension Across MCP, PIP and DIP Joints (Digits II-V)

I.4 Bland-Altman plots

I.4.1 Nuada sensor glove vs Goniometer

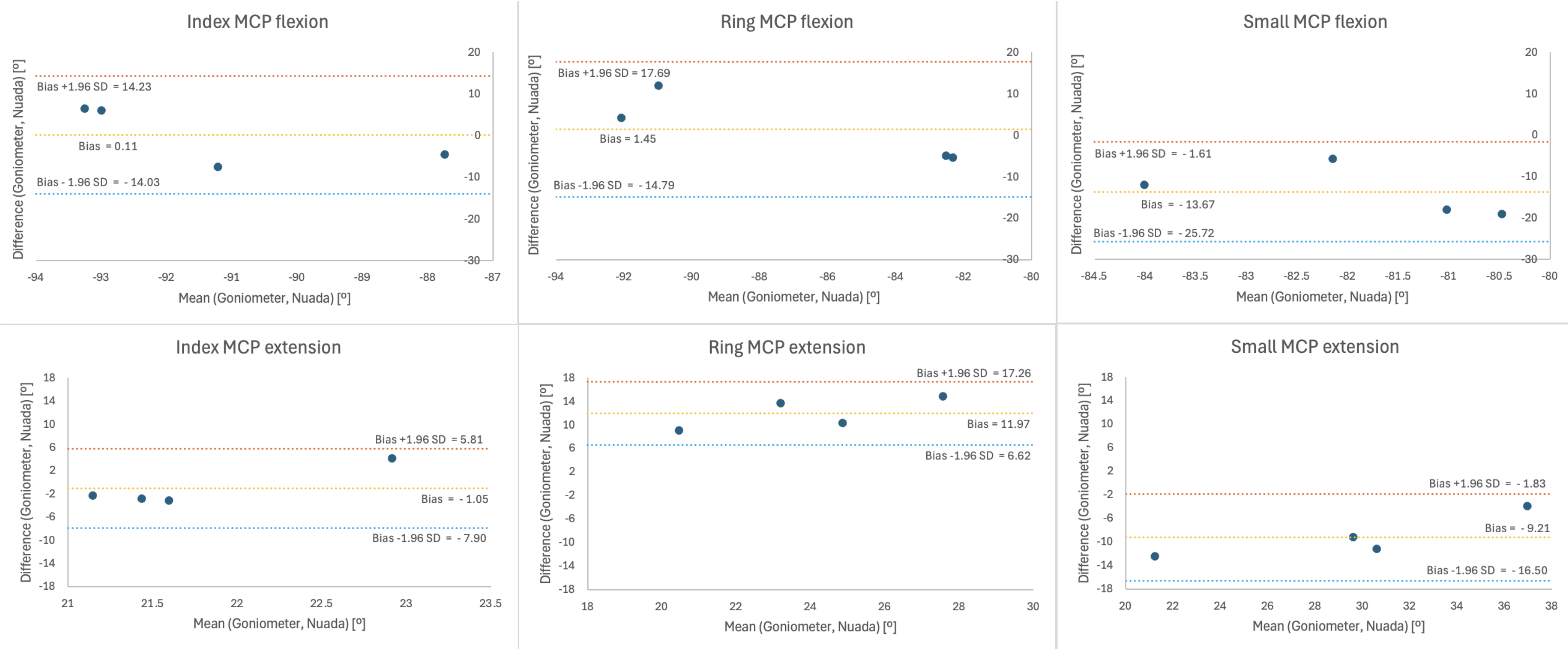

Figure I.2: B&A plots of MCP finger joints' values

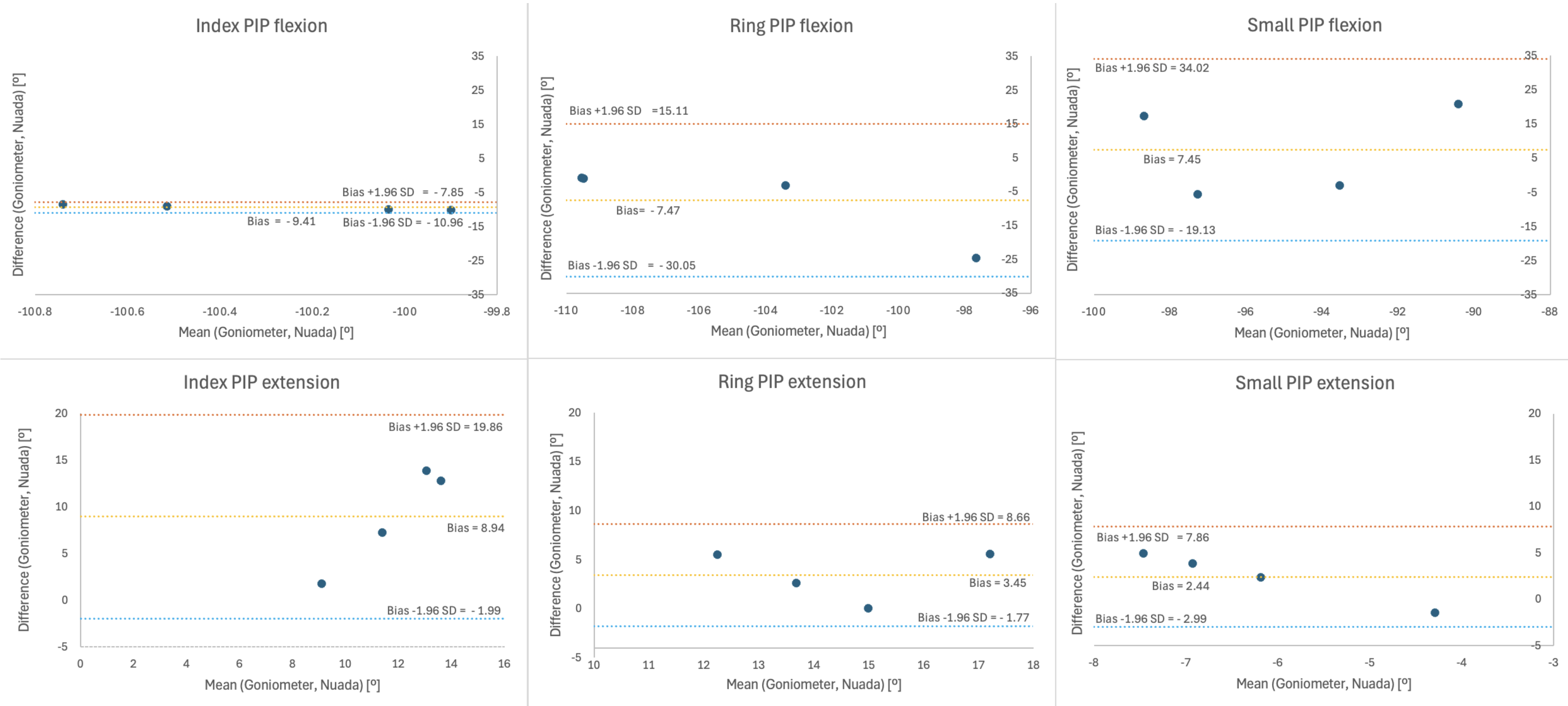

Figure I.3: B&A plots of PIP finger joints' values

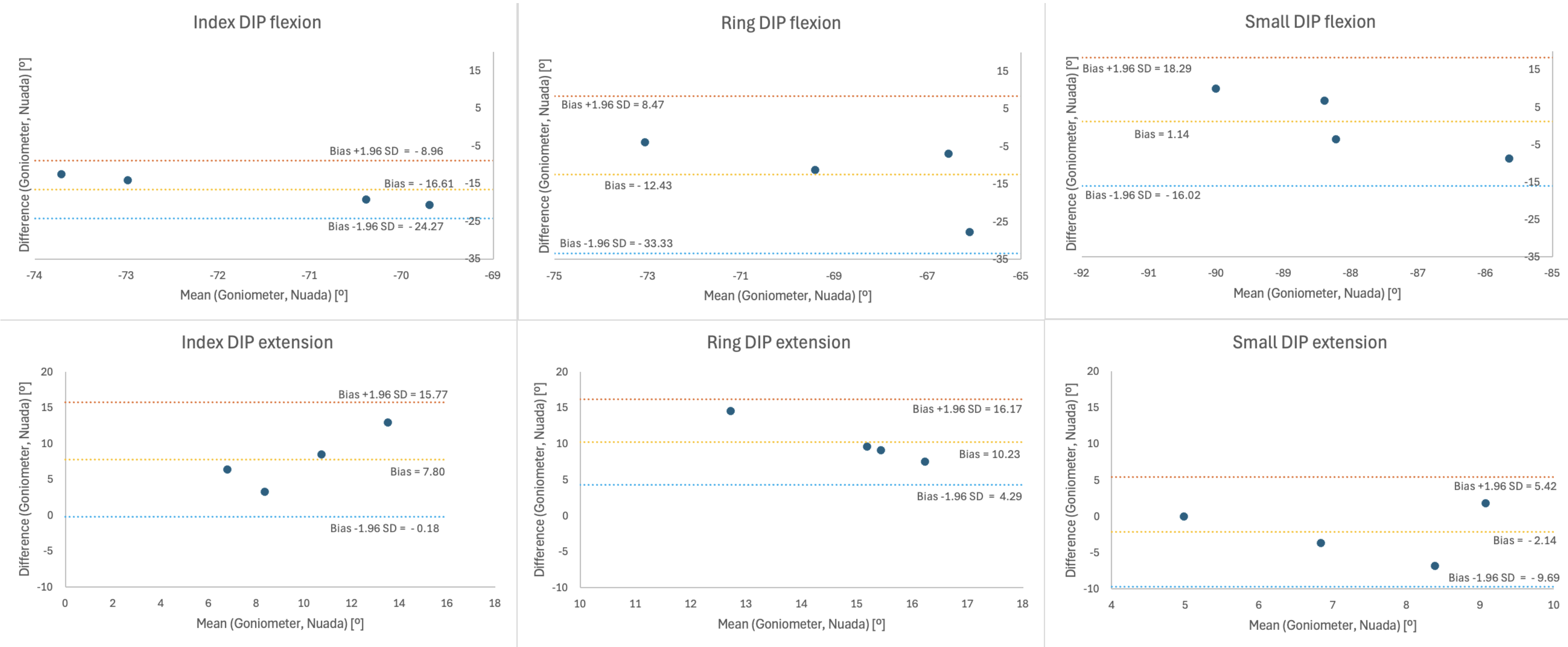

Figure I.4: B&A plots of DIP finger joints' values

I.4.2 UltraLeap vs Goniometer

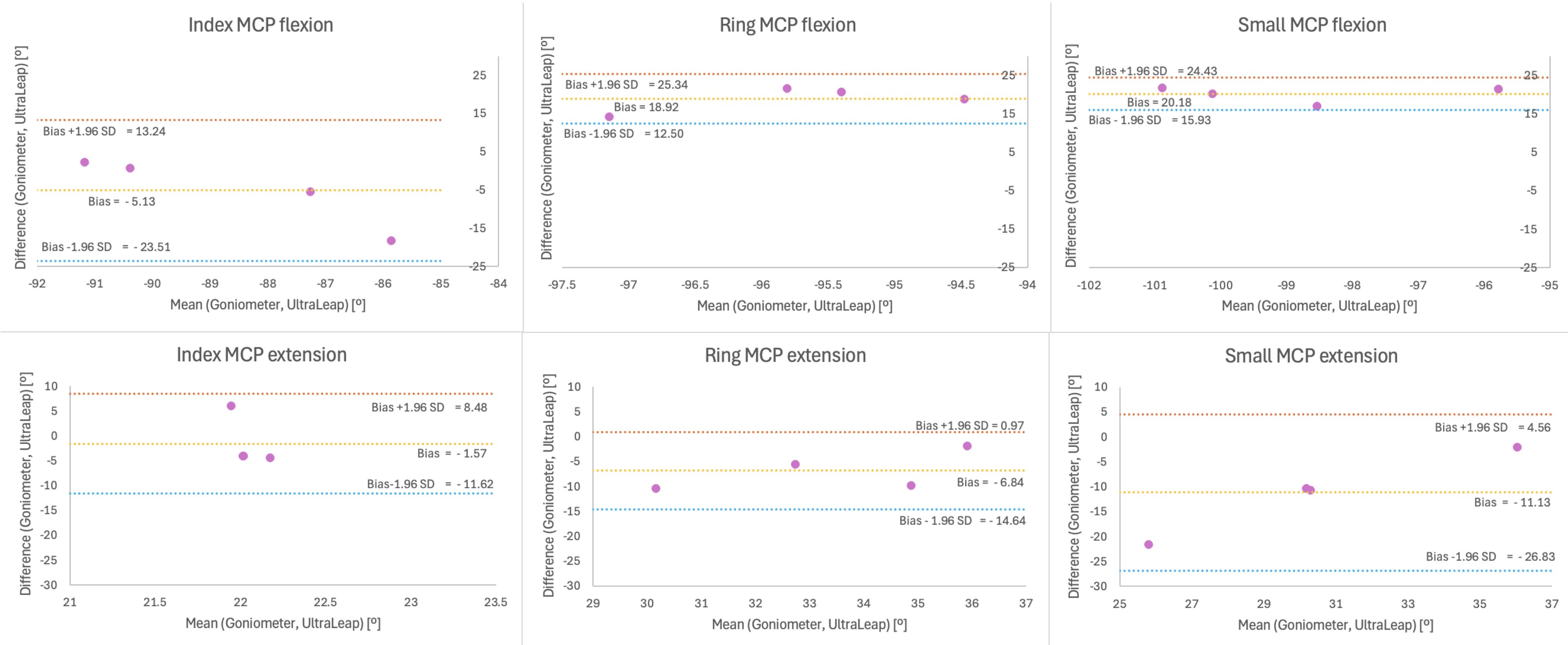

Figure I.5: B&A plots of MCP finger joints' values

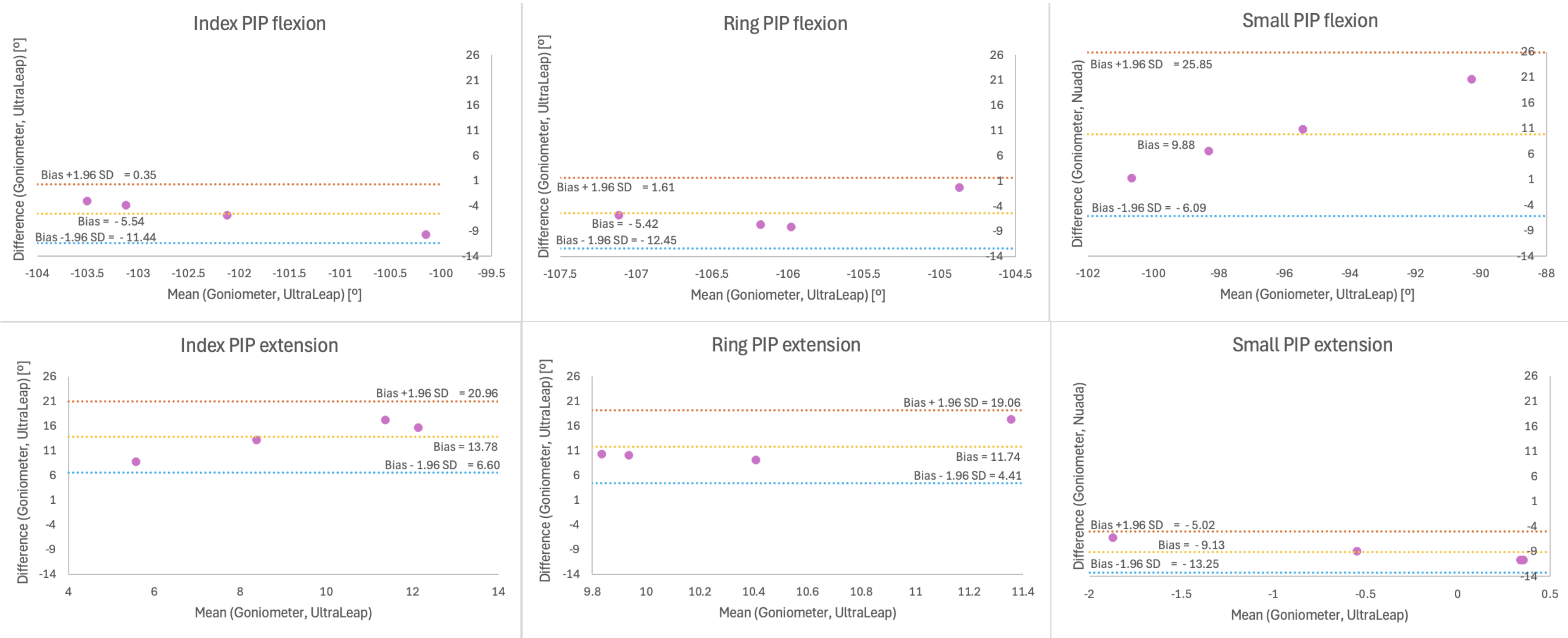

Figure I.6: B&A plots of PIP finger joints' values

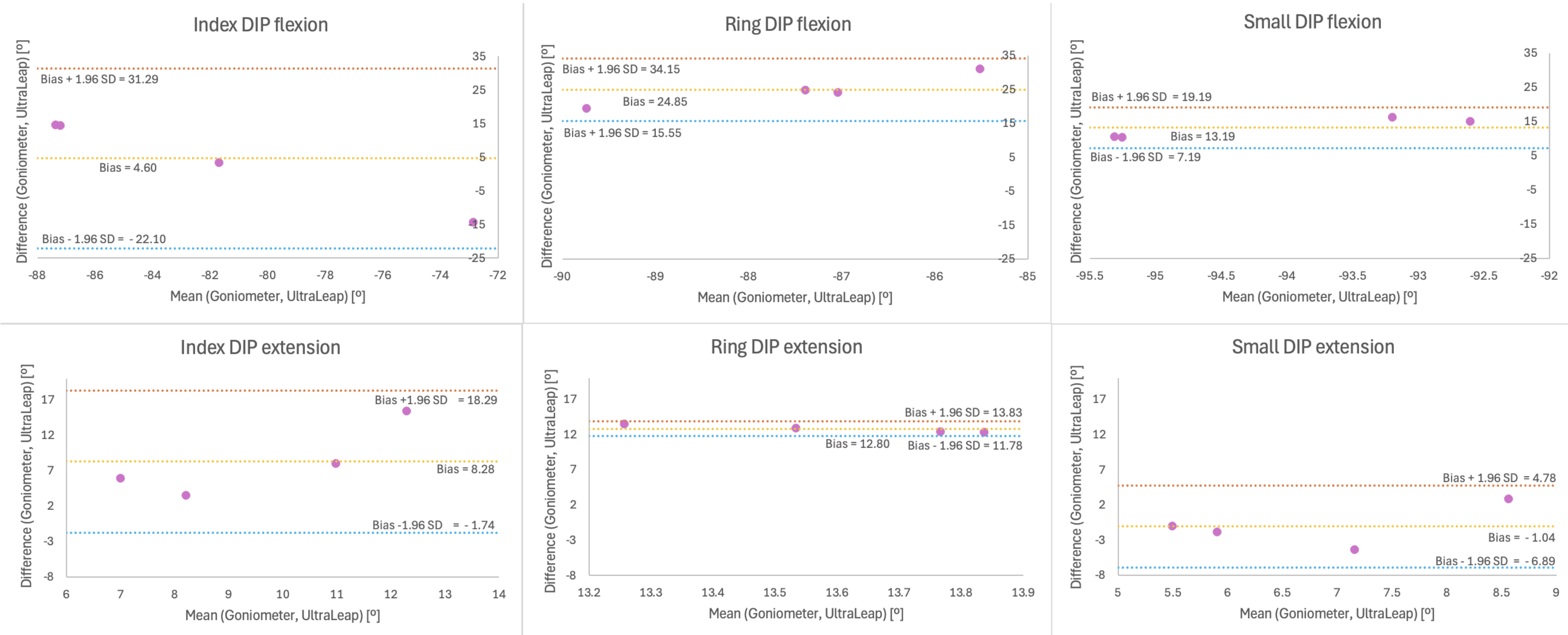

Figure I.7: B&A plots of DIP finger joints' values

I.4.3 UltraLeap vs Nuada

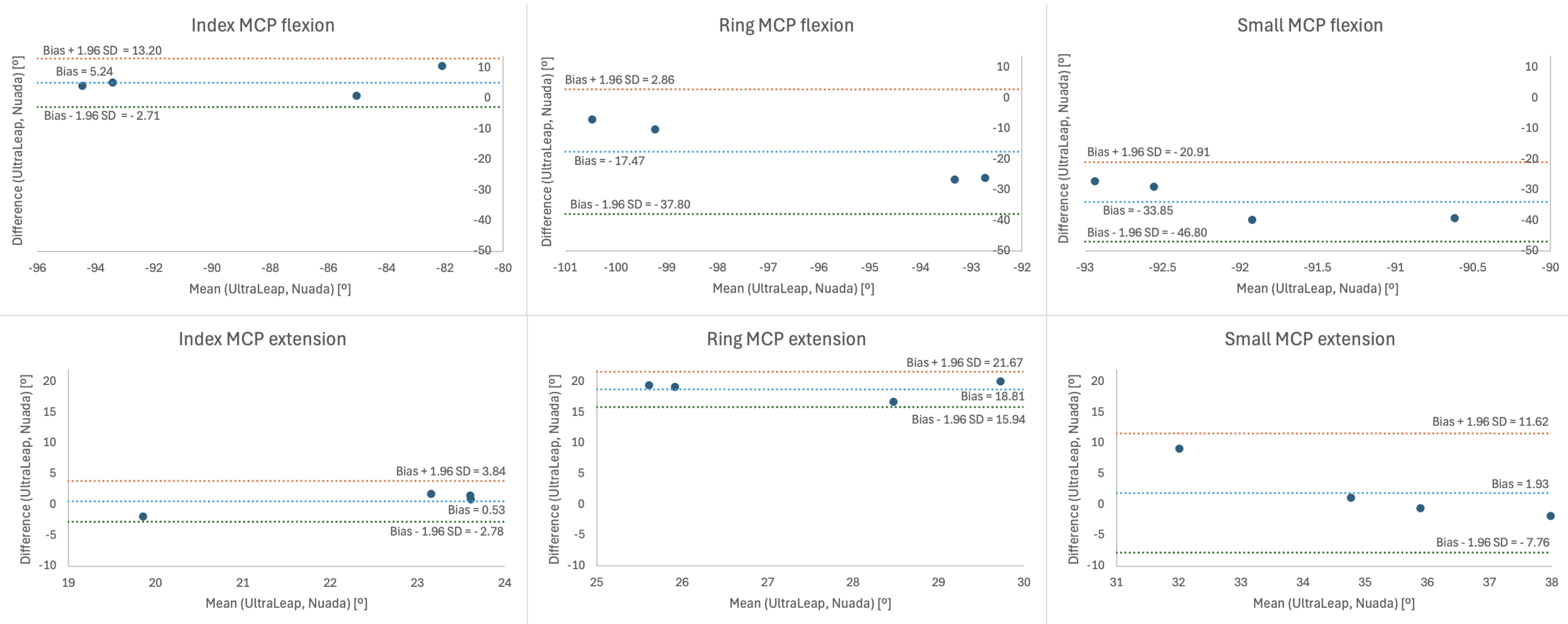

Figure I.8: B&A plots of MCP finger joints' values

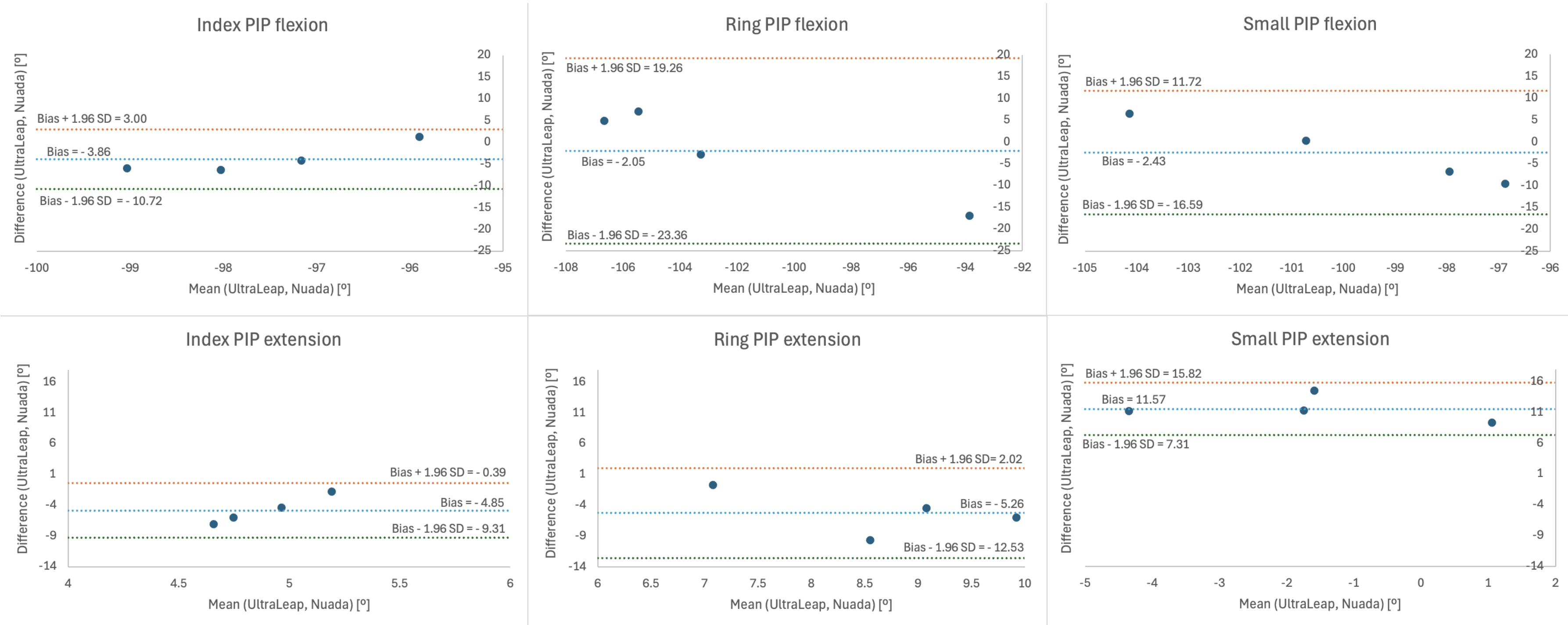

Figure I.9: B&A plots of PIP finger joints' values

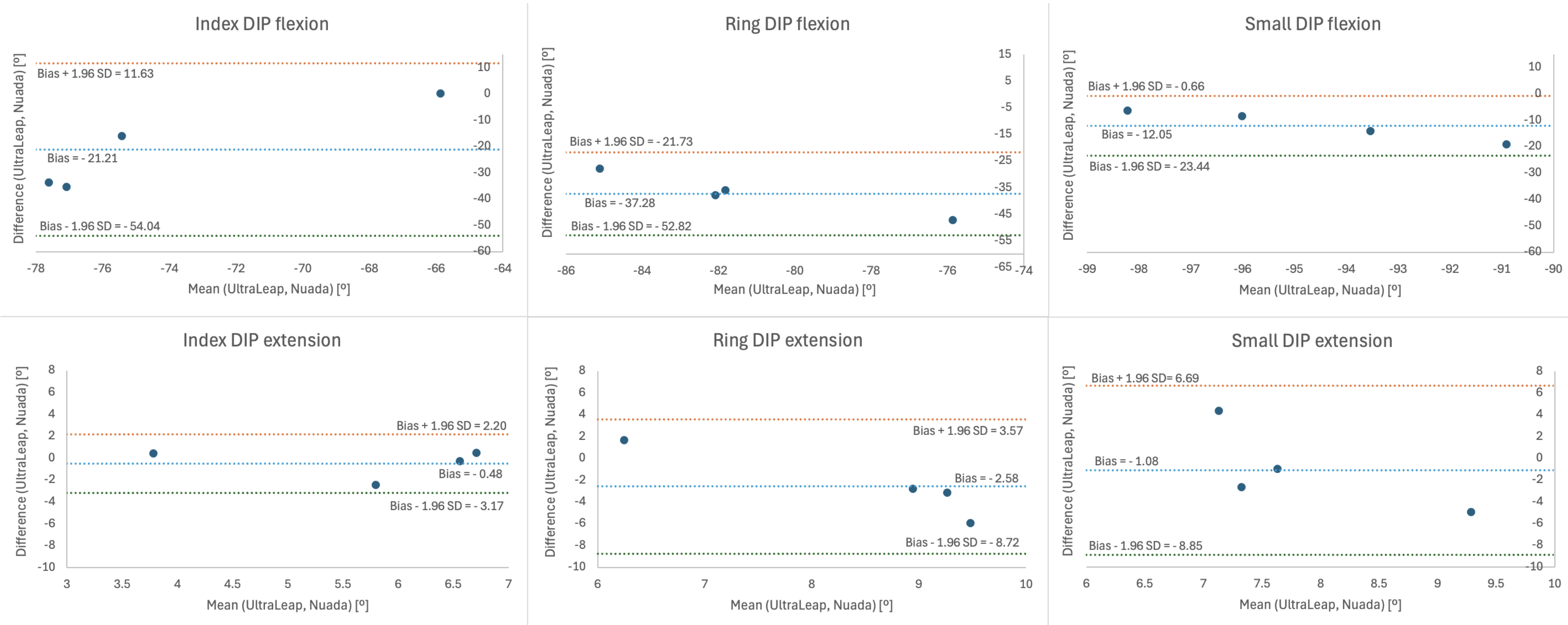

Figure I.10: B&A plots of DIP finger joints' values