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DEGREE PROJECT IN MEDICAL ENGINEERING,

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Validation of a new iPhone application for measurements of wrist velocity during actual work tasks

MOHAMMED ABAID

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STOCKHOLM, SWEDEN 2022

VALIDATION OF A NEW IPHONE APPLICATION FOR MEASUREMENTS OF WRIST VELOCITY DURING ACTUAL WORK TASKS

VALIDERING AV EN NY IPHONE-APPLIKATION FÖR MÄTNING AV HANDLEDSHASTIGHET UNDER VERKLIGA ARBETSUPPGIFTER

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Abstract

The breakthrough in mobile technology and the development of smartphones, supplied with sensing devices such as Inertial Measurement Units (IMUs), has made it possible to obtain accurate and reliable data on the angular velocity for different objects. The available technical sensors for wrist movements, such as electrogoniometers, are costly, time-consuming, and need a particular computer program to be analyzed. Therefore, there is a need to develop user-friendly risk assessment methods for wrist angular velocity measurements. This master thesis aimed to validate the accuracy of a newly developed iPhone application (App), *"ErgoHandMeter,"* for wrist velocity in actual work tasks, by comparing the *"ErgoHandMeter"* to standard electrogoniometers. The project study was performed with four participants, two females and two males, from three jobs performing actual work tasks. The total angular velocity obtained by the mobile application was compared with the angular velocity data from the standard electrogoniometer. The total angular velocities obtained from the smartphone and the goniometer were computed at the 10th, 50th and 90th percentile for the four subjects. The 50th percentile of goniometer-flexion velocity (G-flex) was 7.4 ± 5.4°/s, for the goniometer-total (G-tot) 8.7 ± 6.5)°/s and for App 7.2 ± 4.9°/s. The correlation coefficient for the 50th percentile of goniometer-flexion (G-flex) parameter and smartphone application was 0.994. For the goniometer-total (G-tot) and the application, it was 0.993. In a Bland-Altman plot the mean difference between G-flex and App for the 50th percentile was -0.18 °/s and for G-tot and App was -1.54 °/s, i.e. the App was lower in average. The limit of the agreement between G-Flex and App, and G-tot and App stayed within two standard deviations. For G-Flex and App (mean+1.96SD) was 1.34 °/s, (mean-1.96SD) was -1.71 °/s, while for G-tot and App (mean+1.96SD) was 1.89 °/s, (mean-1.96SD) was -4.96 °/s, indicating an adequate agreement between the two methods. A limitation was that the included occupations were all relatively low velocity. However, in conclusion, the results indicate that the two methods agree adequately and can be used interchangeably.

Keywords: Angular velocity, goniometer, inertial Measurement Unit (IMU), “ErgoHandMeter”, percentile, correlation

Sammanfattning

Genombrottet inom mobiltekniken och utvecklingen av smarttelefoner med sensorer som t.ex. tröghetsmätningsenheter (IMU) har gjort det möjligt att få exakta och tillförlitliga uppgifter om vinkelhastigheten för olika objekt. De tillgängliga tekniska sensorerna för handledsrörelser, t.ex. elektrogoniometrar, är dyra, tidskrävande och de samplade signalerna kräver ett särskilt datorprogram för att analyseras. Det finns därför ett behov av att utveckla användarvänliga riskbedömningsmetoder för mätningar av handledens vinkelhastighet. Syftet med detta examensarbete var att validera noggrannheten hos en nyutvecklad iPhone-applikation (App), "ErgoHandMeter", för handledshastighet i verkliga arbetsuppgifter, genom att jämföra "ErgoHandMeter" med vanliga elektrogoniometrar. Projektstudien genomfördes med fyra deltagare, två kvinnor och två män, från tre yrken som utförde verkliga arbetsuppgifter. Den totala vinkelhastigheten som erhölls av mobilapplikationen jämfördes med vinkelhastighetsdata från standardelektrogoniometern. De totala vinkelhastigheterna som erhållits från smarttelefonen och goniometern beräknades vid den 10:e, 50:e och 90:e percentilen för de fyra försökspersonerna. Den 50:e percentilen för goniometer-flexionshastigheten (G-flex) var i genomsnitt 7,4°/s och för goniometertotalen (G-tot) 8,7°/s. Korrelationskoefficienten (r) för den 50:e percentilen för goniometer-flexionsparametern (G-flex) och smartphone-applikationen var 0,994. För goniometer-total (G-tot) och applikationen var r 0,993. I en Bland-Altman-plot var den genomsnittliga skillnaden mellan G-flex och appen för den 50:e percentilen -0,18°/s och för G-tot och appen -1,54°/s (App var lägre än Gon). Medelvärdet för differensen mellan G-Flex och App och G-tot och App ligger inom två standardavvikelser. För G-Flex och App (medelvärde+1,96SD) var 1,34 °/s, (medelvärde-1,96SD) var -1,71 °/s, medan för G-tot och App (medelvärde+1,96SD) var 1,89 °/s, (medelvärde-1,96SD) var -4,96 °/s. Vilket tyder på en tillräcklig överensstämmelse mellan de två metoderna. En begränsning var att de inkluderade yrkena alla hade relativt låg hastighet. Sammanfattningsvis visar dock resultaten att de två metoderna stämmer väl överens och kan användas på ett utbytbart sätt.

Nyckelord: Vinkelhastighet, goniometer, (IMU), "ErgoHandMeter", percentil, korrelation

DEDICATION

I dedicate this work with love to

KTH

My Parents

My wife

My daughters

My beloved country Sudan

Acknowledgments

First, I want to express my deepest thanks to ***Professor. Mikael Forsman****. It would have been challenging to finalize this project without his support and genuine Knowledge of the subject area.*

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Mohammed Abaid, June 2023

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List of Abbreviations

App	Mobile Application
ANOVA	Analysis Of Variance
BMI	Body Mass Index
Borg CR-10	The Borg Category-Ratio scale
Borg RPE	Borg Rating of Perceived Exertion Scale
CTS	Carpal Tunnel Syndrome
CSV	Comma Separated Values
Devi	*Devi is donated* to the Radial-Ulnar deviation
Flex-Ext	Flex is donated to Flexion-Extension velocity
G-flex	Goniometer flexion
G-tot	Goniometer total
IMU	Inertial Measurement Unit
M/F	Male/Female
MSDs	Musculoskeletal Disorders
NIOSH	National Institute for Occupational Safety and Health
PLIBEL	Plan för Identifiering av Belastningsfaktorer (Method for the identification of musculoskeletal stress factors)
WMSD	Work-related Musculoskeletal Disorder
VIDRA	Video and Computerized Work Analysis

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1. Introduction

Despite the technological advances in ergonomic tools design, assessing and measuring hand postures and movements are costly and hard to perform. To date self-reports and observation methods are the most common tools [1]. However, with the development of electronic sensors such as accelerometers, gyroscopes, magnetometers, and barometric pressure sensors, combined with modern smartphones, enables researchers and practitioners to accurately assess wrist movements and avoid observation methods [2]. Additionally, traditional technical measurements for wrist movement, such as electrogoniometers, are also costly and time-consuming and need specialized software and personnel to perform analyzes [3].

By description, occupational injuries and health problems occur when the mechanical workload is higher than the load-bearing capacity of the components of the musculoskeletal system. Therefore, several factors in workplaces, such as mechanical overload, repetitive work, exposure time, awkward work postures, forceful exertions, and heavy lifting are risk factors for musculoskeletal disorders [4]. A poor work environment is one of the main risk factors that can limit individual life and their capacity to carry out work [5]. About 1.71 billion workers worldwide experienced musculoskeletal problems due to physical and repetitive work [6]. Physical exertion at work and work-related musculoskeletal disorders (WMSDs) have been shown to correlate to each other [4], and wrist movements during repetitive work are one of the main reasons for wrist work-related disorders [7]. Importantly, it has been suggested that to prevent myalgia, tendon disorders, and nerve entrapments in the upper musculoskeletal system, the 50th percentile of wrist angular velocity movement should not exceed 20°/s during a workday [8].

The standard electrogoniometers method is one of the most accurate and reliable methods for measuring wrist movement, although time-consuming and costly [9]. Therefore, this project aimed to measure wrist angular velocity in real work situations with a newly developed iPhone application (ErgoHandMeter) and compare results with the electrogoniometers, as novel and inexpensive method for assessing and measuring wrist movement.

1.1 Aim and objectives

The aim of this thesis was:

- To compare and validate a newly developed iPhone application, *"ErgoHandMeter*," for wrist velocity in actual work tasks to a standard electrogoniometer.

2. Background

2.1 Anatomy of the Wrist Joints

The wrist joint consists of several small joints, and their primary function is to connect the hand to the forearm, making it flexible and allowing us to move our hands with two degrees of freedom. The wrist joints connect the forearm to the hand and allow for a range of motions necessary for daily activities that maintain a physiologic level of inherent stability [10]. The wrist has two big forearm bones and eight small bones known as carpals; the wrist also contains tendons and ligaments, which are connective tissues, tendons connect muscles to bones, and ligaments connect bones. The wrist joints have a total of 27 bones [11]. The two bones running from the elbow to the wrist are *the radius* bone (which runs along the thumb side of the hand). In contrast, *the ulna* bone (runs on the same side along the little finger) and the true joints of the wrist and hand are the *Radiocarpal joint, Midcarpal joint, Carpometacarpal joint (thumb), Carpometacarpal joint (fingers), Metacarpophalangeal joints and Interphalangeal* [12].

2.2 Wrist Movement

The wrist joints have two degrees of freedom to allow for flexion-extension and radioulnar-deviation [12].

Neutral position: Neutral position refers to a position where no major forearm muscles are engaged in maintaining posture.

Flexion and extension: For the wrist, flexion means that the wrist is flexed towards the palm while flexing in the other direction refers to extension (dorsal flexion). The wrist flexion and extension are performed between the radiocarpal articulation and the intercarpal articulation. During wrist flexion, most of the motion occurs in the midcarpal joint and is accompanied by minor ulnar deviation and supination of the forearm [13]. On the other hand, during wrist extension, most of the motion happens at the radiocarpal joint and is accompanied by slight radial deviation and pronation of the forearm [13]. Wrist flexion is the process of twisting the hand palm down towards the wrist, while an extension of the wrist is raising the hand, as seen in Fig.1. The range of motion of the wrist extension is between 70-80 ^{0}, while the range of motion of the wrist for the flexion is 75-85 ^{0} [14].

Radial and Ulnar Deviation: are anatomical expressions of motion that explain the wrist's movement in the perpendicular plane. These directions have been named relative to two bones in the forearm. *Radial deviation* refers to the bending of the wrist towards the thumb (radial bones). In contrast, the *ulnar deviation* is the opposite of radial deviation and refers to the bending of the wrist towards the little finger side [13]. Radial/ulnar deviation occurs in the frontal plane along the anteroposterior axis, whereas wrist flexion occurs in the sagittal plane along the frontal axis [13]. The range of motion for the radial deviation is 15-20 ^{0}, while the ulnar deviation is 30-40 ^{o} [14].

2.3 Angular velocity

The angular velocity of an object describes the object's angular displacement with respect to time. The symbol for the angular velocity is omega (ω) and is measured in angles per unit of time. The relationship between the angular velocity and the rotation angle is expressed according to the following expression: $\omega = (\Delta\theta/\Delta t)$ [14].

2.4 Musculoskeletal Disorders (MSDs) and work-related health problems

Good ergonomics can lead to a win-win situation for both workers and their organization, i.e., reduced costs, improved quality and productivity of work, increased employees job satisfaction and well-being, and improved usability of tools and equipment in the workplaces. Wrist injuries during work can be prevented through proper ergonomic design, such as maintaining a neutral posture, avoid repeated or sustained flexion and ulnar deviation [15].

Ergonomics is about the interaction between people, work, and the surrounding environment. Poor ergonomics can lead to discomfort, sickness, and injuries resulting in musculoskeletal disorders and work-related illnesses. Ergonomics has been defined in different ways. The International Ergonomics Association, 2006 defines the term Ergonomics as:

"The scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design to optimize human well-being and overall system performance." [16].

Musculoskeletal disorders (MSDs) or work-related health problems/injuries affect muscles, joints, tendons, and other supporting tissues leading to pain and reduction in the normal range of activity [17]. MSDs are among the most common causes of ill health and absence from work in Europe, contributing to substantial costs for society [18], and are an increasing healthcare issue globally. MSDs are the second leading cause of disability, after mental and behavioral disorders [18]. In a study by AFA Insurance in Sweden, MSDs are among the most common problems of work-related injuries in Sweden (Swedish Work Environment Authority, 2013), and MSDs were responsible for 71% of work-related health problems in Sweden [19].

The most common types of wrist injuries and work-related disorders are carpal tunnel syndrome, ganglion cysts, tendinitis, trigger finger, and tenosynovitis. The latter are strongly linked to work-related factors such as repetitive work and strenuous postures [20, 21].

2.5 Risk for Developing MSDs

Different workplace factors can lead to the development of MSDs, such as workplace design, the speed and frequencies of tasks, and the weight of the lifted objects. Additionally, psychosocial factors related to the workplace may also influence the development of MSDs.

Different types of physical work can lead to the development of MSDs. In this report, we focus on restaurant work, food delivery tasks and office work. According to the European Agency for Safety and Health at Work, cleaning tasks can be physically demanding. It is recommended that cleaning tasks should be performed with special care to exposures that may lead to developing low back and neck pain, shoulder, and upper limb disorders [22].

As stated by the European Agency for Safety and Health, the main risk factors for musculoskeletal disorders for cleaners are awkward postures, high application of forces, repetitive movements and insufficient rest periods, static workloads, working in constricting space, and poor ergonomics design of equipment handles [22]. Kumar & Kumar (2008), in a systematic review, concluded that cleaning tasks are physically demanding and associated with "high physical load, mental disorder, societal stigma, and psychosocial stresses" [23]. Similarly, MSDs are prevalent among drivers, such as transport drivers, delivery drivers, truck drivers, agricultural truck drivers, forklift drivers, bus drivers, and taxi drivers. The main risk factors for developing MSDs in driving jobs include awkward posture, manual handling, heavy lifting, strenuous tasks, vibration, and repetitive tasks. Commonly, drivers develop MSDs in the lower leg, lower back, shoulder, upper arm, and upper back [24]. Furthermore, restaurant workers are also likely to develop MSDs due to repetitive work and awkward postures. A Cohort study showed that among 52,261 Chinese restaurant cooks the lower back is the most affected area of the body [25].

2.6 Methods for MSDs risk assessment

2.6.1 Self-Reports and Observation

Risk assessment is one of the essential tools to protect employees from developing MSDs. Risk assessment is the first step for control measures, interventions, and promote improvements aiming to reduce MSDs. In the field of ergonomics, there are different methods to assess MSDs, such as self-reports, observations, and technical measurements.

Self-reports are one of the most common methods. Self-reporting includes questionnaires, surveys, checklists, interviews, and focus groups. Self-reported methods are quick, cost-effective, and are easily used for a large population [26]. However, self-reports are subjective, based on the participants' experiences to express their pain perception or exposure. Thus, self-reports may lead to subjective biases affecting their reliability and validity. In a study by Åkesson et al. (2001) for measuring the exposure time of vibration in dental hygienists, showed that there was an overestimation for the exposure duration time when using self-reports compared to direct measurements when using a time-registration device [27]. Viikari et al. (1996) also demonstrated that the self-assessments of the physical workload factors using questionnaires and logbooks showed an overestimation of self-reports compared to observations made by a trained physiotherapy [28].

PLIBEL, NIOSH discomfort questionnaires and the Dutch Musculoskeletal Survey are other examples of self-report surveys to allow the ergonomist to assess musculoskeletal discomfort [29]. In addition, there are other subjective methods to assess different levels of musculoskeletal discomfort among workers, such as the Borg RPE scale, Borg CR-10 scale, body map, and Video and Computerized Work Analysis (VIDRA) [30].

On the other hand, observation is one of the practical objective methods for data collection. There are two types of observations, direct and indirect observation. Direct observation refers to when the observer is directly present in the workplace and observes the situation by taking notes and completing checklists. In contrast, indirect observation occurs when data is collected automatically through films and analysis is performed later [30].

2.6.2 Technical measurements

Technical measurements are more reliable methods than self-reports and observation because they are based on experimental data, and the data will quickly be analyzed using different computer programs and software. Many direct methods use electronic sensing technology to record physical motions and movements in the ergonomic field.

Electrical goniometers

Twin-axis goniometers are one of the technical methods to measure wrist angular velocity. To measure wrist movements, the end-blocks of the goniometer are attached to the dorsal surface of the hand; one end block is attached over the third metacarpal, and the second end block is attached over the midline of the forearm, with the wrist in a neutral position [31]. Goniometers transform the angular position into a proportional electrical signal and provide two outputs simultaneously representing the wrist flexion/extension and radial/ulnar deviations [31].

Inertial Measurement Units (IMUs)

The breakthrough in mobile technology and the "smartphone", supplied with advanced computing and sensing devices such as accelerometers, gyroscopes, and inertial measurement units (IMUs), have made it possible to measure the angular velocity of different objects [32]. An IMU sensor using a combination of accelerometers, gyroscopes, and sometimes magnetometers can provide up to nine degrees of freedom (triple-axis gyroscope, triple-axis accelerometer, and triple-axis magnetometer). The accelerometer measures forces from velocity changes and gravitation [33]. Today they are all tri-axial. This, because they measure the gravity-vector and can estimate their inclination, i.e., the angle relatively the vertical line.

Gyroscopes, however, are used to measure rotation/angular velocity about three axes (x, y, and z) [32, 33]. Movesense is an Inertial Measurement Unit (IMU) designed in Finland by Suunto. It consists of 9-axis motion sensors: acceleration, gyroscope, and magnetometer, and is capable of measuring any movement through open APIs that enable the development of unique in-device apps [34].

3. Materials and Methods

3.1 Participants

For the present study, four participants (2 females and 2 males) were recruited in Stockholm, Sweden. All participants were right-handed, in good health, and free of pain or discomfort in the dominant wrist/hand. Before starting the experiment, all participants were informed about the research, and all signed informed consents. Anthropometric data of participants is shown in (Table. 1).

Table.1 **Participants' anthropometric data. Data is shown as mean (±SD)**

Age (years)	**Height (cm)**	**Weight (kg)**	**BMI (kg/m^2)**
39 (±14)	169 (±15)	75 (±21)	25 (±4)

3.2 Measurements

In this study, two methods were used for wrist total angular velocity measurements. The first method is a newly developed app, *"ErgoHandMeter,"* connected with IMU sensors. The second method is the standard electrical goniometer, which is referred to as goniometer in this report.

3.2.1 Electrogoniometers

A twin-axis goniometer was used to measure wrist angular velocity for two hours actual work tasks (Fig.1). The end blocks on each side of the flexible spring were placed using double-sided tape on the dorsal surface of the hand. One sensor was positioned on the third metacarpal of the hand, and the second was positioned on the midline of the forearm with the arm in a neutral wrist position.

The twin-axis goniometers transform angular position into a proportional electrical signal (voltage signals) that permit the simultaneous measurement of angles in two planes, e.g., wrist flexion/extension and radial/ulnar deviation. The angular rotation of one end-block relative to the other about axis X-X is measured by one channel. Similarly, the second channel measures the rotation of one end block relative to the other about axis Y-Y. The signals obtained from the goniometer were sampled with a sampling frequency of 20 Hz and received by a TMSI mobi8 data logger equipped with an SD memory card (Fig.2). During the experiments the data logger was placed into a waist-belt holder.

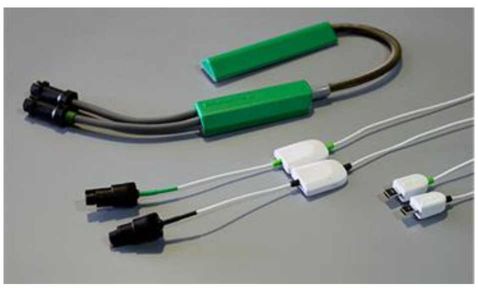


Fig.1 Twin-axis goniometers

Fig.2 TMSI mobi8 datalogger

3.2.2 ErgoHandMeter App & Inertial Measurement Unit (IMU)

The "ErgoHandMeter" application, Fig.3a, was connected to IMU sensors with built-in gyroscope to enable measuring the wrist angular velocity about three axes (x, y, and z). The IMUs unit used in this study is the Movesense developed by Suunto, Finland (Fig. 3b). The Movesense consists of a 9-axis motion sensor (acceleration, gyroscope, magnetometer) and is capable of measuring different movements. To accurately measure wrist velocity, the two IMU sensors were attached to the end blocks of the goniometer. One Sensors were attached side-by-side, one on the top of the goniometer placed at the level of the third metacarpal bone of the hand, whereas the second sensor was positioned on the midline of the forearm with the hand in a neutral wrist position. After each measurement, a comparison between measurement data for wrist angular velocity according to the recommended action levels (20°/s as a median over a working day) was performed and stored in the App as 50th and 90th percentiles. All the Gyroscope raw data in x, y, z and total angular velocity was saved in the ErgoHandMeter application in a CSV formatted file and were used for further analyses.

(a) (b)

Fig. 3 (a) ErgoHandMeter mobile application, (b) the Movesense IMU

3.3 Experimental setup and tasks evaluation

At the beginning, the participants were informed about the experiment and the instruments which are going to be used. Using double-sided tape, the goniometers and IMU sensors were attached to the 4 participants' right hands. At the beginning of the experiment, the participants kept their wrists in 0°/neutral position for 30 sec, as seen in the example, Fig.4. After that, participants performed their regular work tasks. Before the measurement ended, the participants were asked again to hold their wrists at 0°/neutral position for 30 seconds.

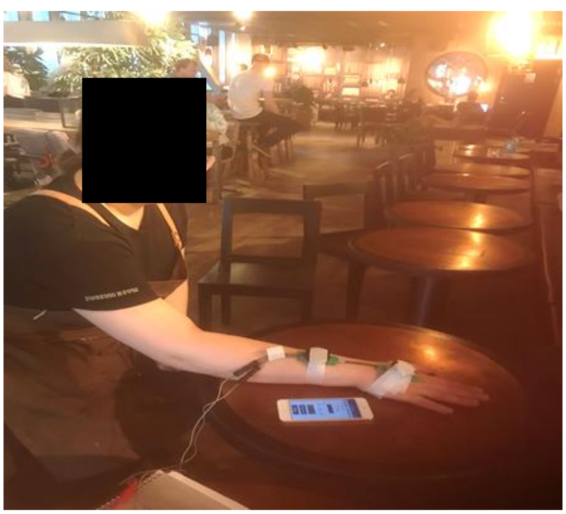
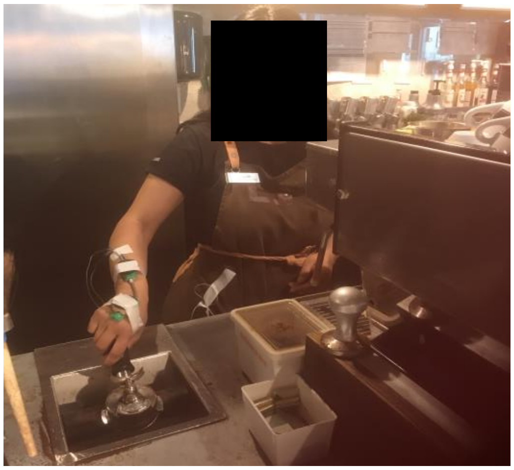
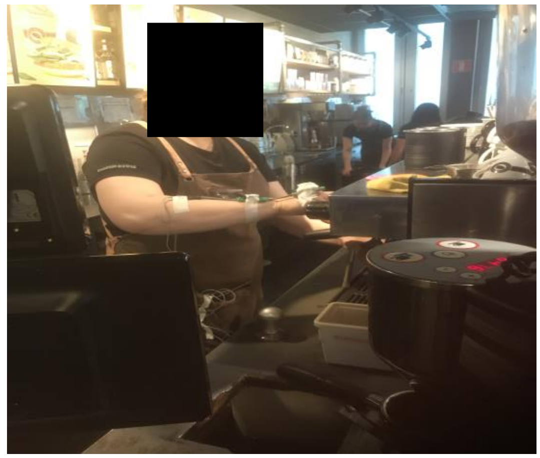


Fig.4 Participants position their wrists in 0° / neutral position

The wrist angular velocities were measured for two hours for each participant during their regular work tasks. Figure.5 a, b, and c showed examples of the participants’ everyday tasks.



(a)



(b)

(c)

Fig.5 a, b and c. Participants when they were doing their everyday work tasks (a and b restaurant works and c represents car food delivery work)

3.4 Data processing

To compare signals obtained by the two methods (i.e., goniometer electrical signal and IMU sensors motion signals), data were processed according to the steps described in the following two sections, and finally the wrist velocity data (°/s) obtained by the goniometers were matched to the same frequency of the App velocities data.

3.4.1 Goniometer

Electrogoniometer data was transmitted to the memory card of the TMSI mobi8 datalogger, then the goniometer data was processed in MATLAB (R2021a, MathWorks, Natick, MA, USA). Firstly, the .smp files recorded in the memory card of the TMSI data logger are converted into dataLog files, and the angles data files were read into MATLAB. The goniometers simultaneously provide two output signals, one for the wrist flexion/extension (G-Flex) and the one signal for the radial/ulnar deviations (G-Dev). Angular velocities signals obtained from Goniometer-flexion (G-flex) and Goniometer- deviation (G-Dev) were separated into two columns in the dataLog Files. Then, Goniometer-total angular velocity (G-tot) was computed by the differentiation of angle value for 20 Hz sampling frequency, individually for flexion (G-flex) and deviation (G-dev), and the total angular velocity, and were calculated for each sample according to the following formula:

$$G - tot = \sqrt{v_{G-flex}^2 + v_{G-dev}^2} \qquad (1)$$

Where $V_{G\text{-flex}}$ denoted flexion velocity and $V_{G\text{-}dev}$ to radial-ulnar deviation velocity.

3.4.2 ErgoHandMeter App data processing

Data processing was performed with the mobile App “ErgoHandMeter”. The gyroscope data of each sensor is sampled at a frequency of 50 Hz and transmitted via low-energy Bluetooth from the sensors to an iPod Touch. All data for the angular velocity was stored and saved in the device as .csv files. After each measurement, the raw data and the angular velocity were displayed in the App as separate .csv files, which were used for further analysis. Additionally, the App provides statistical results summaries such as mean value and 50th and 90th percentiles. Within the app, the wrist velocity is computed as an absolute angular velocity of the lower arm sensor subtracted from the velocity of the hand sensor [35].

3.5 Statistical analysis

Statistical analyses were performed in SPSS 29.0 (IBM, Chicago, IL, USA).

3.5.1 The one-way ANOVA (Analysis of Variance)

The one-way analysis of variance (ANOVA) is used to compare the means between the studied groups and determine if any of those means are statistically significantly different. In this project, one-way ANOVAs were performed to assess possible differences between G-flex. G-tot and App for the 10^{th}, 50^{th} and 90^{th} percentile of angular velocities [36]. A planned contrasts test was performed to test for differences between the mean of the 50^{th} percentile of angular velocity for G-tot and App.

In ANOVA, the null hypothesis is that there is no difference among the studied group means. If any one of the groups significantly differs from the overall group mean, then the ANOVA test indicates a statistically significant outcome (p-value < 0.05). When the p-value is > 0.05, this implies there is no significant difference between the two methods.

3.5.2 Correlation Coefficient

The correlation coefficient was used to assess the strength and the direction of the linear relationship for the angular velocity obtained from the two methods (goniometer data and "ErgoHandMeter"). A zero-correlation coefficient indicates no linear relationship between two continuous variables, and a correlation coefficient of -1 or +1 indicates an ideal linear relationship between the variables [37].

3.5.3 Bland-Altman plot

Bland-Altman plots are widely used to identify the similarities between two quantitative methods. The Bland-Altman graph is plotted by taking the difference between the two measurements along the Y-axis and the mean of the two measurements along the X-axis.

In this study, the two measurements investigated were the total angular velocities obtained by the mobile application "ErgoHandMeter" from IMU sensors and the angular velocity obtained from the goniometer measurements. The difference between the wrist angular velocity between the two methods was plotted in the Y-axis. The average of the angular velocities of the two methods were represented in the X-axis. In the Bland-Altman plot, the mean difference value for the two measurements was located on the middle line of the graph. The limit of an agreement was calculated by taking the mean and two standard deviations (SD) of the difference between the App angular velocity and the goniometer's velocity [38].

In this project, the actual work tasks performed by the 4 participants at 50^{th} percentiles are used to plot the Bland-Altman plot between App and goniometer velocities (G-flex & G-tot).

4. Results

4.1 Angular velocity

Figures 6 & 7 show an example of the wrist velocity (degree/s) for the actual work tasks performed by participant 1 (restaurant worker) measured by the two methods.

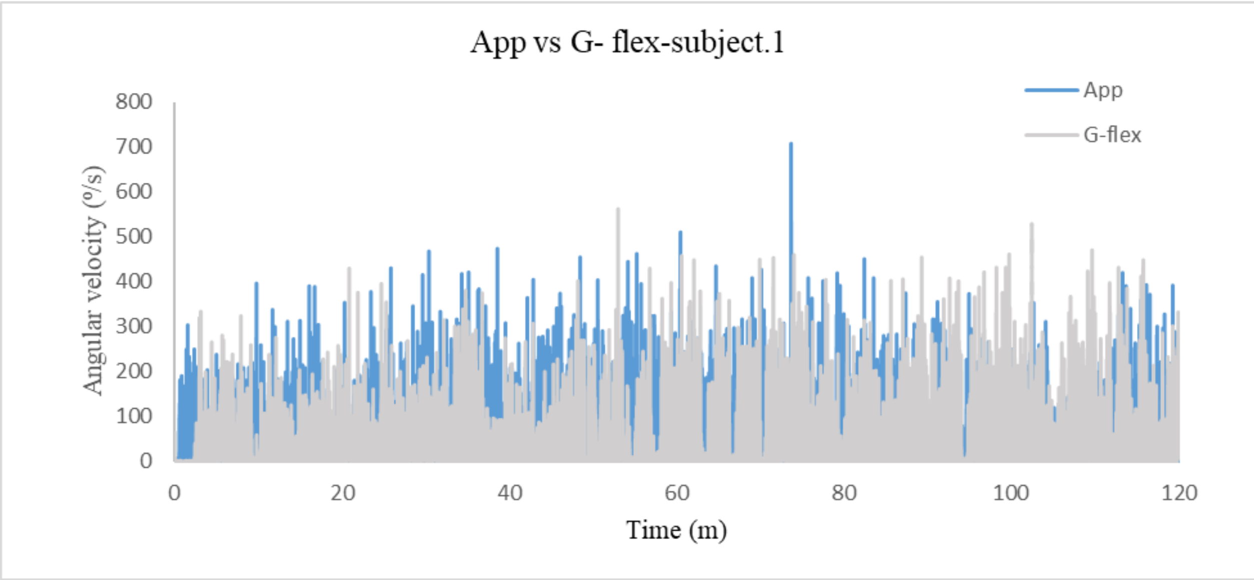


Fig.6 Wrist velocity (degree/s) for participant 1 (restaurant worker) [App vs. G-flex]

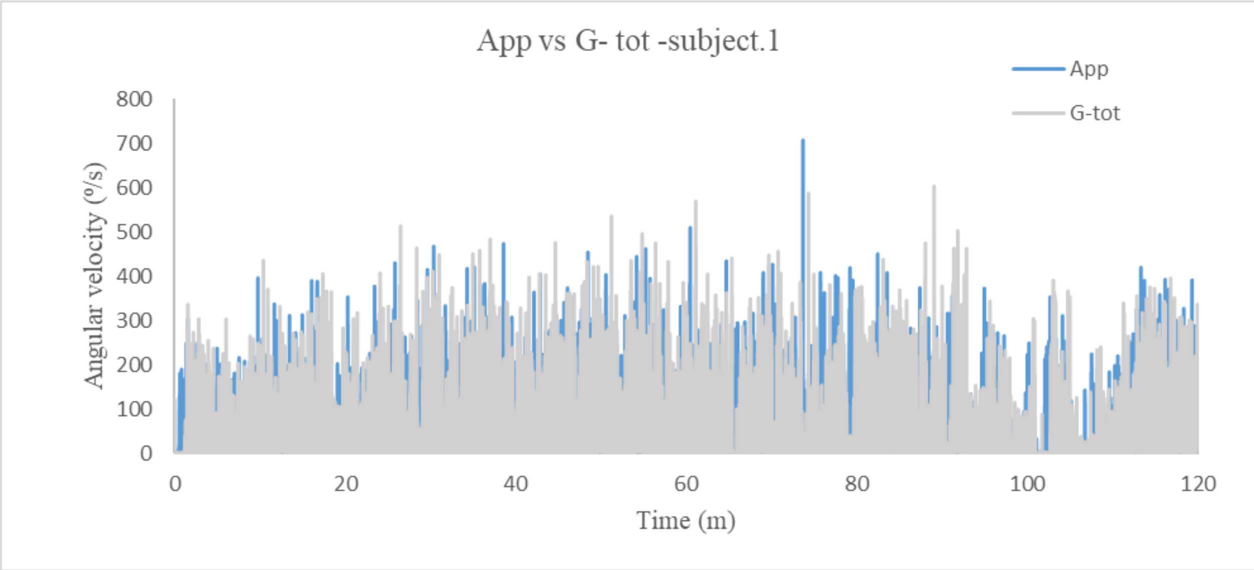


Fig.7 Wrist velocity (degree/s) for participant 1 (restaurant worker) [App vs. G-tot]

4.2 Percentiles of wrist angular velocity (degree/s) obtained by the two methods

The "ErgoHandMeter" mobile application measures the total wrist velocity. In this study we are interested to see how the percentiles results of G-Tot and App agreed with each other. Additionally, comparisons were also made between G-Flex and App, because in normal tasks, the influence of radial/ulnar deviations velocity (G-Dev) is very low compared to G-Flex.

Table.2 shows the 10th, 50th and 90th percentiles of wrist velocity (°/s) for G-flex, G-tot and App for the four subjects**.**

Table.2 Percentiles of wrist angular velocity (°/s) and results of p-values (**the 50th percentiles are in bold).**

Subjects	**Percentiles**	**G-Flex**	**G-tot**	**App**	***p*-value**
(Mean ± SD) for subjects at 10th, 50th and 90th percentile	10th	(0.2 ± 0.3)	(0.3 ± 0.3)	(0.8 ± 0.2)	0.03
	50th	**(7.4 ± 5.4)**	**(8.7 ± 6.5)**	**(7.2 ± 4.9)**	**0.92**
	90th	(60.1 ± 27.8)	(69.1 ± 34.3)	(57.0 ± 29.6)	0.85

The planned contrasts test showed no significant differences between G-tot and App ($p = 0.7$).

4.3 Correlation

Figures 8 and 9 show the correlation plot for the 50th percentile of the App "ErgoHandMeter" and G-flex for the real works tasks measured by the two methods.

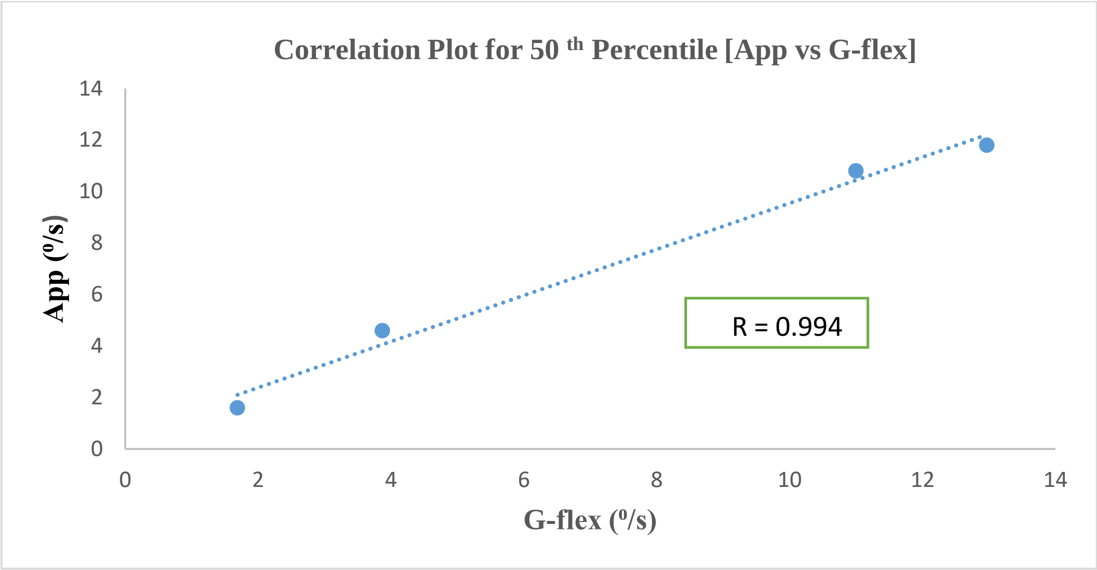


Fig.8 Correlation Plot for 50th percentile of angular velocity between App and G-flex. R is the calculated Pearson correlation coefficient.

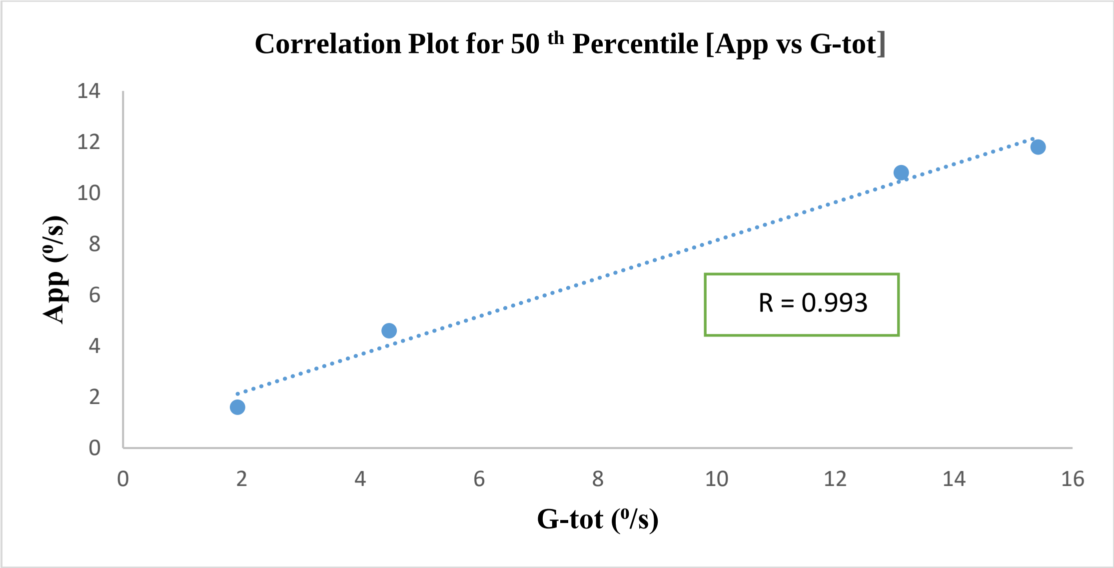


Fig. 9 Correlation Plot for 50th percentile of angular velocity between App and G-tot. R is the calculated Pearson correlation coefficient.

4.4 Bland-Altman Plot

Figures 10 and 11 represent the Bland-Altman plot comparing the angular velocity of App vs. Gon-flex and App vs. Gon-tot for the work tasks performed by the 4 participants at the 50th percentile. Y-axis = difference between the 50th percentile of App "ErgoHandMeter" and Goniometer data (°/s), where X-axis = mean App "ErgoHandMeter" and Goniometer data (°/s).

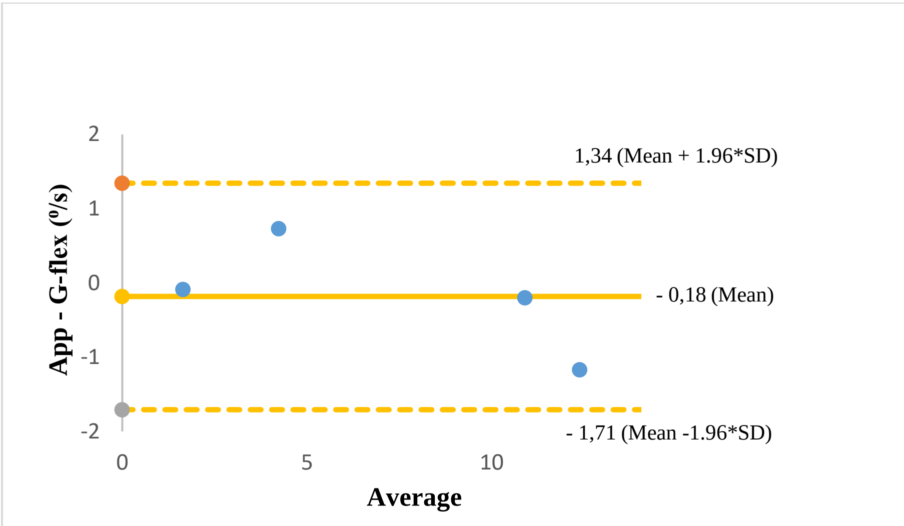


Fig. 10 Bland-Altman for App and Gon-flex angular velocity at the 50th percentile

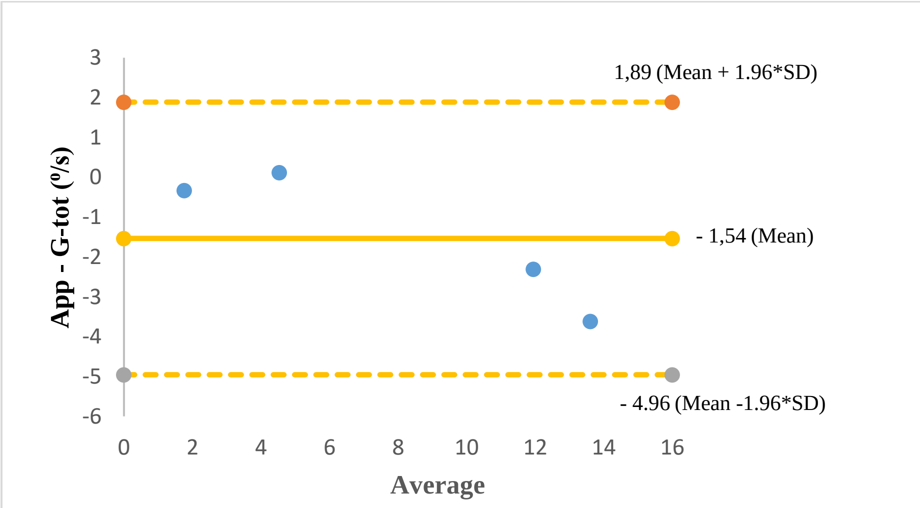


Fig. 11 Bland-Altman for App and G-tot angular velocity at the 50th percentile

5. Discussion

The study's main objective was to validate the wrist angular velocities obtained from the newly developed App (ErgoHandMeter) in actual work tasks with the standard goniometer. The research project was performed in three workplaces where workers used low force exertions.

As seen in both Fig 8 and Fig 9, the angular velocity profiles of wrist (°/s) vs time, for the actual work tasks, obtained by the two methods show similar trend during the work time (2 hours). Fig. 8 represents the angular velocity of App vs. G-flex for participant .1, while Fig. 9 represents the wrist angular velocity (°/s) of App vs G-tot for the same participant.

When comparing the App angular velocity with the goniometer angular velocity at the 10^{th}, 50^{th}, and 90^{th} percentile for the four subjects (table 2), results of percentiles indicate that the angular velocities obtained from the goniometer data and App are related to each other, especially when comparing the percentiles of G-flex with App velocity. Moreover, the 50^{th} percentile of total angular velocity (degree/s) obtained by the App and G-total using a one-way ANOVA planned contrasts test demonstrated no significant differences between the G-tot and App ($p = 0.7$). However, care must be used when interpreting data since there was a tendency for differences, with only four subjects.

The correlation coefficient (r) between the 50^{th} percentile of G-flex and App is 0.994 (Fig.8), and between G-tot and App is 0.993 (Fig.9). There was a strong positive linear relationship between the two measurements evaluated.

Reliability results for App and G-flex angular velocity at the 50^{th} percentile (Fig. 10), shows that the mean difference between the two methods was - 0.18 (°/s), whereas for App and Gon-tot angular velocity at the 50^{th} percentile (Fig. 11) was -1.54 (°/s). Although the App and G-flex angular velocity at the 50^{th} percentile had a smaller mean difference in relation to App and Gon-tot angular velocities, the obtained values of angular velocities of App and G-tot were spread closer to the mean. The mean differences lied within two SD and did not exceed the maximum allowed difference between the two methods. Hence, we deem the methods can be used interchangeably for App and G-tot. Our results, however, are not similar to Manivasagam and Yang when they were evaluated wrist velocity by Movesense sensors and electrical goniometers [39]. Their measurements were recorded using Movesense Showcase v.1.0.5, an iOS mobile phone application already developed by Suunto (Suunto, Vantaa, Finland), and they were found that iOS mobile application was largely overestimating the G-flex. In the measurements, there is still some slight variation between the values of the obtained total angular velocity when comparing the two methods (App & Goniometer). I am not completely sure about the reason for the discrepancy in results, but the highest total velocity (G-tot) obtained by the goniometer compared to App total velocity could be due to crosstalk errors as explained by Hansson et al. (2004) [40]. Cross-talk may possibly make velocities be counted both as flexion-extension velocities and deviation velocities; when the total velocity is computed it may then be too high. But that does not explain the close to zero bias between the total velocity from and the App and the flexion velocity from the goniometer, so it is still difficult to see the reason for the discrepancy.

Moreover, several recent studies [39, 40, 41, 42, 43] on technical measurements including Goniometers, IMU sensors, Electromyography, and Optical Motion Tracking Systems demonstrated that these methods provided accurate and reliable results for measuring muscle activity and body motion. However, in a master's thesis by Tesfaldet (2020), evaluating IMU sensors against optical motion tracking system, the author found significant differences between sensor's velocity and the obtained velocity of the markers during flexion movements of the wrist. The author was not certain about the main reason for these differences and so are we, thus it is an important suggestion to further investigate the reasons for the above differences [44].

6. Conclusion

In conclusion, this master thesis aimed to validate a newly developed iPhone application, "ErgoHandMeter," for wrist velocity in actual work tasks by comparing the "ErgoHandMeter" to a standard electrogoniometer. Even though, small sample sizes decrease the statistical power increasing the chances of a type II error, the results of velocities from goniometer data and App suggest that the two methods are in good agreement and can be used interchangeably, especially when comparing G-flex velocity to App total velocity. We strongly encourage, however, further research with larger sample sizes.

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Appendix A

Division of Ergonomics, KTH Royal Institute of Technology
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Information letter for volunteers in this project

Validation of a new iPhone application for measurements
of wrist velocity during real work tasks

What is the goal of this research project?

This research project aims to compare the results of wrist angular velocity in actual work tasks using a newly developed app connected with inertial measurement unit (IMU) sensors and the conventional method for measuring wrist angular velocity, "*electrogoniometers".* The purpose of this study is to validate and check the accuracy of the newly developed App in order to be used as a user-friendly risk assessment method since it is easy to be used and not expensive compared with today's methods, which have been used in the field for measuring wrist movements. The risk assessment is a systematic approach to control and eliminate work-related accidents and helps prevent work-related injuries.

How will the research project be conducted?

The participants' right hands will be attached to two Movesense inertial measurement units (IMU sensors). The first sensor will be taped on the back of the hand with double-sided tape, and the second on the lower arm as a watch with an armband. Simultaneously, electric twin-axis goniometers will be attached in the same positions as the IMU sensors. The end block/ sensor of the goniometer will be attached to the back of the hand (positioned on the third metacarpal of the hand). In contrast, the goniometer's other end block /sensor will be positioned on the midline of the forearm with the arm flat on a table surface (neural wrist). First, the participant will be familiarized with how to use the instruments before the experiment starts, and then the recording will start while participants perform their everyday work tasks. The entire study is expected to take 2 hours for each participant.

Is participation in the study voluntary?

Yes, participation is voluntary. There is no need to provide a reason in case you decide to stop the tests at any moment. All data you provide in this research project will be kept strictly confidential. The collected data will only be used to validate the newly developed App with "*electrogoniometers"* and develop the technology. The responsible researcher is Mikael Forsman.

How will the results be reported?
The results will be published in scientific journals and presented at scientific conferences. Your identity will always be kept confidential.

I have read the information and understood the purpose of the study and what my participation means, and I agree to participate in this study.

________________________	____________________	__________
Name in print	Signature	Date

Additional consent:
Do you authorize us to take photographs of you during the study for use in written reports, scientific publications, conference presentations, and future grant applications?

Yes ☐ No ☐

If you have any questions, please contact:

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