HAKKI KOSE

IZMIR KATIP CELEBI UNIVERSITY

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IZMIR KATIP CELEBI UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

INVESTIGATION OF WEARABLE MOTION CAPTURE SYSTEM TOWARDS BIOMECHANICAL MODELLING

M.Sc. THESIS

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Thesis Advisor: Dr. Senay MIHCIN

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İZMİR KATİP ÇELEBİ ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

BİYOMEKANİK MODELLEMEYE YÖNELİK GİYİLEBİLİR HAREKET YAKALAMA SİSTEMİNİN ARAŞTIRILMASI

YÜKSEK LİSANS TEZİ

Hakkı KÖSE
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Hakkı KOSE. a **M.Sc.** student of **IKCU Graduate School of Natural And Applied Sciences**. successfully defended the thesis entitled “**Investigation of Wearable Motion Capture System Towards Biomechanical Modelling**” which he prepared after fulfilling the requirements specified in the associated legislations before the jury whose signatures are below.

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Date of Submission : 29.08.2019
Date of Defense : 29.08.2019

To my family,

FOREWORD

First and foremost, I would like to thank to my advisor Dr. Senay MIHCIN for enabling me to do research in the field of biomechanics. I have benefited from her vast knowledge conducting a research project under the light of scientific foundations, which was very motivating and encouring in this MSc thesis.

This thesis was supported by Izmir Katip Celebi University Coordination Office of Scientific Research Projects. I would like to take this opportunity to express my gratitude to all its support in the planning, research, execution and formation of my thesis.

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August 2019

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ABBREVIATIONS

MOCAP	Motion Capture
MCSs	Motion Capture Systems
IMUs	Inertial Measurement Units
RMSE	Root Mean Square Error
ROM	Range of Motion
BOB	Biomechanics of Body
VH	Visual Hull
MLD	Moving Light Display

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INVESTIGATION OF WEARABLE MOTION CAPTURE SYSTEMS TOWARDS BIOMECHANICAL MODELLING

ABSTRACT

Motion Capture (MOCAP) is frequently used to study in the field of biomedical engineering, while building biomechanical models in the design of implants, in the field of ergonomics, and also in physiotherapy. MOCAP systems provide kinematic data as an output. Biomechanical models use this output as an input for producing kinetic output by measuring the range of motion (ROM) on the joints of human body. For high bio-fidelity modelling, accurate daily life data are required. Here, we asses a novel marker-less wearable MOCAP system. Smartsuit Pro (Rokoko, Copenhagen, Denmark) for feeding in data to a biomechanical modelling software. The suit is utilised out of its intended use, which is utilized normally in the field of digital entertainment as a MOCAP system. OptiTrack (LEYARD, Corvallis, USA) is an optical infrared marker-based motion capture system. This technology uses several cameras, equipped with infrared light-emitting diodes. The infrared light from the cameras is reflected by reflective markers and captured by each camera as 2D point display images. By combining several of these 2D images;the system calculates the 3D position of all the markers within the capture space. A calibration process is needed beforehand to determine the position of the cameras in relation to each other, and in relation to a global coordinate system defined by the user.

In this study, comparison between a wearable MOCAP system SmartSuit Pro and marker based system OptiTrack was completed *in vitro* and *in vivo* experiments to collect evidence about the ROM of the upper extremities of human body. In vitro study, proof of concept for the upper body motion is provided using a skeleton model with its left arm replaced by a custom-made 2 link arm mechanism which integrated DYNAMIXEL, a robot exclusive smart actuator with fully DC motor controller and network and one DC servo module with Arduino software. They are used to send signal to supply the range of motion of the shoulder. Single plane constrained; flexion – extension movements of the shoulder was simulated using a controlled step motor to quantify the deviation between the planned and the measured profile by the wearable suit. Cross validation is completed in vivo using OptiTract. With ethics committee permission, data were collected from 7 male and 7 female healthy volunteers who have no previous history of upper extremity disorder.Three different single plane constrained; abduction movements of shoulder in frontal plane, flexion movements of the shoulder and elbow in sagittal plane and rotation movements of shoulder in horizontal plane. For repeatability and reliability purposes, 9 sets of motions were repeated 3 times to measure flexion/extension of shoulder and elbow joints in the sagittal plane and to measure abduction/adduction of shoulder joints in the frontal plane and to measure internal/external rotation of shoulder joints in the horizontal plane. The relative peak angles were calculated from 3D position data. For in vitro study, Root Mean Square Error (RMSE) was 0.66 and 0.96 degrees respectively Rokoko and OptiTrack in shoulder flexion. In vivo RMSE results for shoulder, abduction movements averagely were calculated as 9.65 and 8.8 degrees respectively Rokoko and Optitrack. The RMSE result of flexion movements of the shoulder and elbow averalgely were calculated as 15.8 and 13.44 degrees between Rokoko and Optitrack. The RMSE result of rotation movements of the shoulder averagely were calculated as 14.29 and 14.49 degrees between Rokoko and Optitrack. Bland- Altman plots showed that Rokoko system produces data comparable to OptiTrack. The collected data was fed into Biomechanics of Bodies (BoB) simulation software for calculating kinetic data. The data was compatible with BOB to run the simulation in offline mode. In conclusion, the results demonstrated that Rokoko system could be an alternative while measuring ROM in clinics and therapy centres with the evidence collected in this study.

BİYOMEKANİK MODELLEMEYE YÖNELİK GİYİLEBİLİR HAREKET YAKALAMA SİSTEMİNİN ARAŞTIRILMASI

ÖZET

Hareket Yakalama (MOCAP), biyomedikal mühendisliği alanında implant, ergonomi ve fizyoterapi tasarımında biyomekanik modeller oluştururken önemli bir adımdır. MOCAP sistemleri çıktı olarak kinematik veri sağlar. Biyomekanik modeller bu çıktıyı insan vücudunun eklemlerindeki hareket aralığını (ROM) ölçerek kinetik çıktı üretmek için bir girdi olarak kullanır. Biyo-aslına uygun modelleme için doğru günlük yaşam verileri gereklidir. Burada veriyi biyomekanik bir modelleme yazılımına beslemek için Smartsuit Pro'ya (Rokoko, Kopenhag, Danimarka) işaretleyici olmayan giyilebilir yeni bir MOCAP sistemi sunuyoruz. Giysiden normalde MOCAP sistemi olarak dijital eğlence alanında faydalanıyor.

OptiTrack (LEYARD, Corvallis, ABD), optik kızılötesi işaret tabanlı hareket yakalama sistemidir. Bu teknoloji, kızılötesi ışık yayan diyotlarla donatılmış kameralar kullanır. Kameralardan gelen kızılötesi ışık yansıtıcı işaretlerle yansıtılır ve her kamera tarafından 2B nokta görüntüleri yakalanır. Bu 2B görüntülerin birkaçını birleştirerek, sistem yakalama alanı içindeki tüm işaretleyicilerin 3B konumunu hesaplar. Kameraların birbirleriyle ve küresel bir koordinat sistemi ile olan ilişkilerini belirlemek için önceden bir kalibrasyon işlemi kullanıcı tarafından tanımlanır.

Bu çalışmada Rokoko ve OptiTrack'in üst ekstremite ROM ile ilgili *in vitro* ve *in vivo* deneyler arasındaki karşılaştırılması incelenmiştir. İn vitro çalışmada üst vücut hareketi için kavramın kanıtı iskelet modeli kullanılarak sağlanmıştır. DYNAMIXEL'in entegre DC motor kontrollü ve ağa sahip DC servo modülünde özel akıllı bir harekete geçiricidir ve Arduino yazılımıyla ağ bağlantısı olan sol kol omuz hareket aralığı sağlamak için sinyal gönderir.Tek düzlem kısıtlı, omuzun fleksiyon - uzama hareketleri, giyilebilir elbise ile planlanan ve ölçülen profil arasındaki sapmayı ölçmek için kontrollü step motor kullanılarak simüle edildi. Çapraz doğrulama, in vivo olarak Optitract kullanılarak tamamlanmıştır. Etik kurul izniyle, daha önce üst ekstremite bozukluğu öyküsü olmayan 7 erkek ve 7 kadın sağlıklı gönüllüden veri toplandı. Üç farklı düzlemle sınırlı; frontal düzlemde omuzun abdüksiyon hareketleri, sagital düzlemde omuz ve dirseğin fleksiyon hareketleri ve horizantal düzlemde omuzun dönme hareketleri, tekrarlanabilirlik ve güvenilirlik amacıyla omuz ve dirsek eklemlerinin sagital düzlemdeki fleksiyon / uzaması, frontal düzlemdeki abdüksiyon/addüksiyonu ve horizantal düzlemde de içsel/dışsal rotasyonları ölçmek için 9 hareket seti 3 kez tekrar edildi. Göreceli tepe açıları 3B konum verilerinden hesaplandı. İn vitro çalışmasında Rokoko ve OptiTrack için Kök Ortalama Kare Hatası (RMSE) omuz fleksiyonunda sırasıyla 0.66 ve 0.96 derece olarak hesaplandı. İn vivo çalışmasında, omzun abdüksiyon hareketlerinin Kök Ortalama Kare Hatası (RMSE) ortalama Rokoko ve Optitrack için sırasıyla 9.65 ve 8.8 derece olarak hesaplandı. Omuz ve dirseğin fleksiyon hareketlerinin Kök Ortalama Kare Hatası (RMSE) ortalama Rokoko ve Optitrack için sırasıyla 15.8 ve 13.44 derece olarak hesaplandı. Omzun rotasyon hareketlerinin

Kök Ortalama Kare Hatası (RMSE) ortalama Rokoko ve Optitrack için sırasıyla 14.29 ve 14.49 derece olarak hesaplandı. Bland-Altman grafikleri Rokoko sisteminin OptiTrack ile karşılaştırılabilir veri ürettiğini gösterdi. Toplanan veriler, kinetik verileri hesaplamak için Vücutların Biyomekaniği (BoB) simülasyon yazılımına beslendi. Veriler, simülasyonu çevrimdışı modda çalıştırmak için BOB ile uyumluydu.

Sonuç olarak, sonuçlar Rokoko sisteminin kliniklerde ve terapi merkezlerinde ROM ölçümleri için çalışmada toplanan kanıtlarla alternatif olabileceğini göstermiştir.

1. INTRODUCTION

Human motion capture was first encountered by Eadweard Muybridge in his famous experiments entitled Animal Locomotion in 1887. Muybridge is considered to be the father of motion pictures for his work in early film and animation. Animal Locomotion was a study into the way in which animals and birds moved. The study included recording at discrete time interval photographs of the subjects in order to visualise motion. In 1973 psychologist Johansson conducted his now famous Moving Light Display (MLD) experiments, into the visual perception of biological motion [1]. Johansson attached small reflective markers to the joint locations of human subjects and recorded their motion. He asked subjects to identify known movements after being shown just the marker trajectories. These experiments were the first few steps into what is becoming an ever increasingly travelled path of research.

Motion capture was developed as a photogrammetric analysis tool in biomechanical research in the 1970s and 1980s [2] and spread to different industries as technology matured. Motion capture is the analysis of a scene giving rise to some mathematical representation of the movement given by a human subject or as Menache writes "Motion Capture is the process of recording a live motion event and translating it into usable mathematical terms by tracking a number of key points in space over time and combining them to obtain a single 3D representation of the performance." [3]. Today, the main markets that benefit from motion capture are medicine [4], sports [5], entertainment [6] and law / surveillance [7]. There are smaller markets that also benefit from technology; for example, motion capture equipment is used to help design ergonomic environments [8]. Additional uses include automobile safety tests in which the movement of crash test dummies is captured and analyzed [9].

Movement is healthy, but we are all exposed to motor loss at some stage in our lives, whether from injury, illness or aging. In this case, we need a retraining, training or rehabilitation process that teaches us to act or exercise in a certain way. In this sense, motion capture (MOCAP) is an opportunity to provide information both directly (the area of motion of a joint) and indirectly (habits, physical inactivity, etc.) [10].

Motion capture systems produce a large variety of data (3D marker trajectory, angular speed, linear acceleration) that is used in life sciences, animation, or engineering domains, MOCAP systems' data are used to derive kinematic and kinetic data during different movements or to analyze muscle activity in different applications such as clinical gait analysis (a standardized clinical examination that involves measurement of a patient's gait pattern in order to identify and understand gait deviations, with the final aim of supporting therapeutic decisions) (CGA) [11] and musculoskeletal modeling [12]. Limitation of laboratory-based 3D motion capture methods is the availability and cost of laboratories, limited measuring area and line of sight problems with markers [13]. In addition, it is not possible to estimate during daily living activities outside the laboratory. These deficiencies have led to the development of algorithms that allow the estimation of ground reaction forces and moments using only kinematic data [14]. Inertial motion capture (IMC) provides an assessment of segment orientation and full-body motion capture in absence of laboratory conditions [15]. Importantly, Xsens IMC system (Xsens Awinda, Xsens Technologies BV, Enschede, Netherlands) has been shown to predict joint angles with good accuracy [16] and was used to predict 3D ground reaction forces and joint moments during gait and provided comparable accuracy to optical motion prediction [17].

There are a number of markets that benefit from motion capture technology for the recording of a person's movement. Within these markets, O'Rourke and Parent [18] acknowledge two broad approaches that are commonly used.

The first approach uses *electromagnetic* sensors placed at the joints that transmit their positions and orientations back to a central processor where the motion is recorded or viewed. The sensors necessitate either cables or wireless transmission to communicate with the central processor. The former requires that the subject be 'tethered' with some kind of cabling harness, whereas the latter requires that the subject carries a power source such as a battery pack [19]. The advantage of electromagnetic sensors is that the three-dimensional position and orientation of each sensor can be recorded and displayed in real time, regardless of posture of the actor. The drawbacks relate to the range of the electromagnetic field, the restricted movement of the subject resulting from the instrumentation required and the global positioning of the subject.For instance, the systems having electromagnetic sensors are increasinglyavailable, from companies such as Xsens Technologies B.V., (Enschede, The Netherlands); Shimmer Sensing (Dublin, Ireland), BioSyn Systems (Surrey, BV, Canada), I Measure U (Auckland, New Zealand), and APDM Wearable Technologies (Portland, OR, USA). The Xsens MVN BIOMECH system is composed of wireless motion IMUs (called MTw2 sensors) and native biomechanical protocols, and estimates three-dimensional joint kinematics [20].

The second approach makes use of reflective markers to triangulate the 3D position of a subject between one or more cameras calibrated to provide overlapping projections. This *optical* approach requires no cables, so potentially permits greater freedom of movement within the studio range of the cameras for the actor. As a network of cameras determines the location of each marker, the global positioning of the subject is easily determined. Depending on the posture of the actor however, many of the reflective markers may be hidden from the view of some of the recording cameras and this occlusion can create problems in the acquisition of data [21]. A disadvantage of the optical approach is that it does not provide real-time feedback and the data can be error prone and noisy. Because orientation information is not directly generated, more markers are required than with magnetic trackers. The spreading of motion analysis means that in addition to market-leading expensive high-end systems, such as Vicon (Oxford metrics, UK), cheaper camera systems appeared that were not specifically meant for scientific purposes, but sneaked in scientific motion labs. One such brand is OptiTrack (NaturalPoint, Corvallis, OR, USA), which was applied to the field of biomechanics from animation motion capture. Its main applications currently include virtual reality (VR), robotics, movement sciences and animations [22]. It has taken time for OptiTrack to become a scientifically accepted and used system as motion labs already rely on their own well-established high-end motion capture systems. The spreading of cheaper systems also requires validation studies that compare the accuracy of new systems with scientific gold standard systems, representing an approach which researchers can relate to other possible important technical aspects of adequacy in a specific application are capture volume, minimum detectable marker size, frequency and resolution of the motion capture system.

Beckerman [23] continues to subdivide these two broad approaches. Electromagnetic motion capture may include mechanical exoskeletal systems that directly monitor body joint angles. These systems are typically rigid structures of metal or plastic rods connected to each other by a potentiometer that hinges at the joints of the body. On the other hand, magnetic systems calculate the position and orientation with the relative magnetic flux of the three orthogonal coils in both the transmitter and receiver. The relative density of the voltage or current of the three coils allows these systems to calculate both range and orientation by meticulously matching the monitoring volume. Markers are not obstructed by non-metallic objects, but are sensitive to magnetic and electrical interference from metal objects and electrical sources in the environment affecting the magnetic field. Inertia systems are based on miniature inertial sensors, biomechanical models and sensor fusion algorithms. Motion data from inertia sensors are usually transmitted wirelessly to a computer where motion is recorded or displayed. Most inertial systems use gyroscopes to measure rotational speeds converted to the joints of a skeleton in the associated software. Inertia systems can capture six degrees of full-body free movement freedom in real time [24]. One of the newer entrants in the inertial space is ROKOKO,which makes a wireless motion-capture body suit that is The Smartsuit Pro boasts 19 sensors dotted around the wearer’s body, with each one including a gyrometer, accelerometer, and magnometer. Algorithms are then able to take this data, make sense of it, and stream it to your device while also storing it in a special ‘hub’ located on the suit itself. The whole setup lasts around eight hours and is rechargeable using a regular USB power bank. Once the data hits your computer it can be manipulated using a number of popular 3D software packages. There are also direct plugins for engines like Unity, Unreal Engine, and MotionBuilder, plus the ability to develop others using Rokoko’s SDK [25].

Assessment of movement patterns during functional activities such as walking and squatting, and during sporting manoeuvres such as jumping, is a cornerstone of musculoskeletal physiotherapy. Commonly, the physical examination involves observation by the clinician and completion of clinician- or patient-rated scales [26]. However, it is challenging to accurately evaluate multiple joints of both legs in multiple planes of movement when an individual is performing a dynamic functional activity, which often occurs at speed. Three-dimensional optoelectronic (camera-based) motion systems can be used to provide comprehensive, objective measurements [27], but this typically requires the patient to attend a specialised movement analysis laboratory. The equipment within these laboratories is expensive, non-portable, and requires a high level of technical expertise and a lengthy calibration process. The use of these systems is therefore not widespread in clinical practice, and clinicians typically do not have access to objective biomechanical information for assessing patient performance. A more rigorous approach to quantifying joint movement in the clinic is required.

A potential solution to this problem is inertial measurement units (IMUs), which could be used in clinical settings to objectively measure movement patterns during functional activities. An IMU is comprised of accelerometers, gyroscopes, and magnetic sensors combined with a fusion algorithm, for example a Kalman filter [28]. It can be attached to a body segment to estimate the movement of that segment in space. When combined with other IMUs on adjacent body segments, the kinematics of movements can be calculated [29]. IMU motion-capture systems are portable and less expensive than traditional camera-based motion-capture systems. The validity of joint kinematics calculated with IMU systems has been confirmed with respect to optoelectronic systems [30].

This chapter demonstrates a strong link between technique and quality of performance and injury from poor technique. The results from the studies studied here demonstrate that there is a desire to use motion capture technology to provide visualization and motion feedback about motion in order to develop a good technique and contribute to performance improvement.

Researchers have reported that there are difficulties with existing motion capture methods in producing a visually pleasing performance; these challenges are common and vary depending on the technology used.

The literature review shows that the development of motion capture methods will provide a clear contribution to produce a visually acceptable representation of motion data in a virtual real-time environment that can be used for the classification and performance analysis of human movement.

The aim of this study was to compare the ROM of the upper extremity movements of the human body with in vitro and in vivo experiments using a wearable MOCAP system Rokoko SmartSuit Pro and the marker-based system OptiTrack.

2. MATERIALS AND METHODS

In this study, comparison between a wearable MOCAP system SmartSuit Pro and marker based system OptiTrack was completed in two steps; first in vitro, and then in vivo. The overall idea is to collect evidence about the ROM of the upper extremities of human body after promising results in vitro. Then, we show how we have processed motion data in order to compare both MOCAP systems.

In vitro study, ROKOKO and OPTITRACK were compared by establishing a platform that can move in a single plane. In vivo studies, volunteers were asked to perform their motions in a single plane to compare the ROKOKO and OPTITRACK.

The data obtained from ROKOKO and OPTITRACK were processed with the help of Matlab and angles were compared.

2.1 In Vitro Study

In vitro study, concept evidence for the upper body motion was provided using a skeleton model with its left arm replaced by a custom-made 2 link arm mechanism. Single plane constrained, flexion - extension movements of the shoulder was simulated using controlled step motor to quantify the deviation between the planned and the measured profile by the wearable suit. A custom-made 2 link arm mechanism integrated DYNAMIXEL, a robot exclusive smart actuator with fully DC motor controller network and one DC servo module with Arduino software. Flexion movements of shoulder showing joint rotations were as in Figure 2.1.

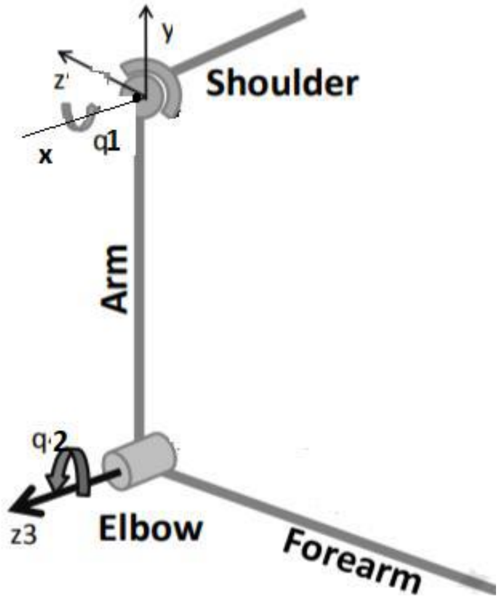


Figure 2.1: Schematic model of the upper limb showing joint rotations.

The joint angles of interest for the shoulder (measured between the back and upper arm) were calculated ROM flexion/extension in the frontal plane. It was expected to observe flexion between 0 -90 degrees with the signals given by Arduino.

Four IMU sensors were fitted to a platform which has DC servo controlled motors.Three optical markers were used for the optical MCS (Optitrack system) after the calibration of systems. The designed platforms for this study can be seen in Figure 2.2.

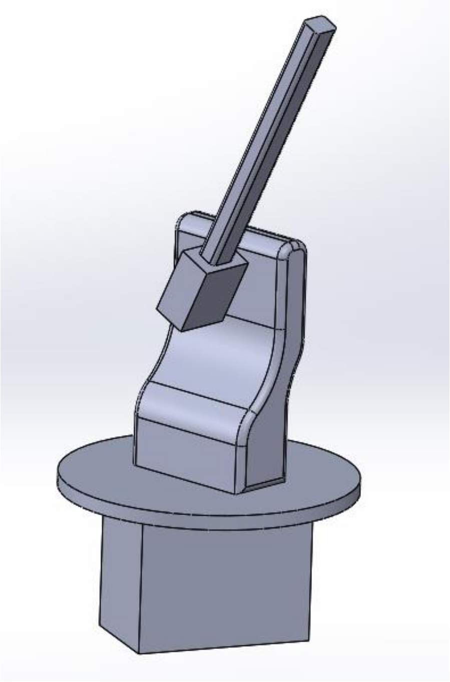


Figure 2.2: The planned platform for in vitro study.

Shoulder joint: Your shoulder joint is a complex system made up of five joints and three bones:

- clavicle, or collar bone
- scapula, your shoulder blade
- humerus, which is the long bone in your upper arm

This system of joints and bones allows your shoulder to move in different directions. Each movement has a different range of motion.The ability of your shoulders to move in a normal range depends on the health of your:

- Muscles
- Ligaments
- Bones
- Individual joints

Shoulder flexion: Flexion is a movement that decreases the angle between the two parts that the joint is connecting. If you hold your arms straight and palms against your sides and raise your arms in front of your body to point your hands at something in front of you, you are practicing flexion.

A normal range of motion for shoulder flexion is 180 degrees. This involves moving your arms from palms against the side of your body to the highest point you can raise your arms over your head as shown in Figure 2.3.

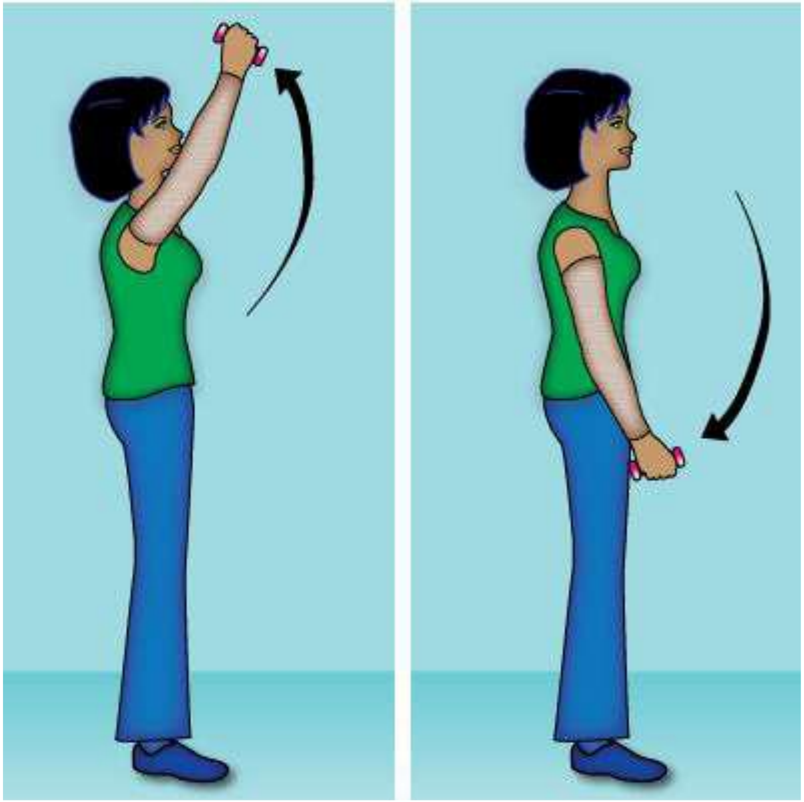


Figure 2.3: Single joint movements of shoulder flexion.

Elbow Flexion: Flexion of the elbow refers to the movement of the elbow joint that brings the two proximal bones closer together. When the elbow is flexed, the angle between the two joined bones is reduced. Flexion of the elbow is an anatomical term of motion and may also be called elbow flexion. Repetitive motion of the elbow or prolonged holding of a single position may increase the risk for work related musculoskeletal injuries. Steps should be taken with proper safety procedures and ergonomic design to mitigate this risk. The elbow joins the upper arm and forearm. The synovial hinge joint of the elbow connects the humerus of the upper arm to the ulna and radius of the lower arm. The elbow is limited to a single plane of motion, flexion, and extension.

Flexion of the elbow occurs when the lower arm was pulled toward the upper arm, causing the angle between the two to become smaller, while extension is the reverse motion of unbending. The collection of muscles that control elbow flexion are referred to as the flexor group. The brachialis found in the upper arm is the primary muscle responsible for elbow flexion. Injury or strain to the muscles in the flexor group or the elbow joint can impair flexion of the elbow as in Figure 2.4.

Figure 2.4: Elbow flexing is done by placing one hand on the patient's wrist and the other on the upper arms, slowly bending the elbow until the hands touch the shoulder.

Shoulder abduction: Abduction occurs when you have arm movement away from the middle of your body. When you raise your arm out from the sides of your body, it’s an abduction of your shoulder. A normal range for abduction, starting with your palms at your sides, is around 150 degrees in a healthy shoulder. This places your hands above your head with your arms straight as Figure 2.5.

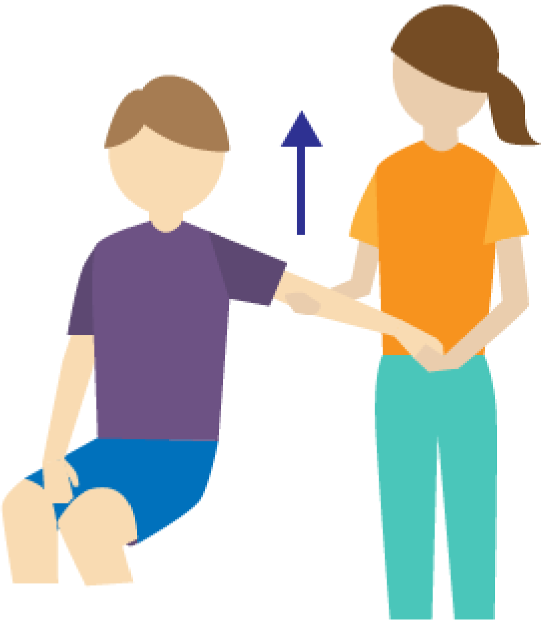


Figure 2.5: Shoulder abduction is slowly move the arm upwards, making sure the palm is facing down once you go above shoulder height. Bring their arm reach to level of their head, and then slowly lower it back down.

Internal rotation: With your arms at your sides, turn your palms towards your body and bend your elbows 90 degrees so your hands are pointing in front of you. Hold your elbows towards your body and slide your arms towards your body. This is internal rotation - also called medial rotation - and the normal range of motion for a healthy shoulder is 70 to 90 degrees as in Figure 2.6.

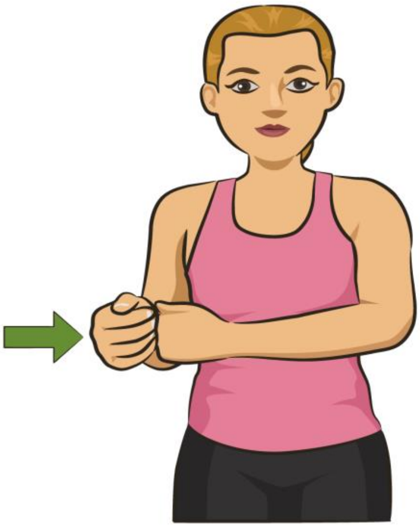


Figure 2.6: Internal rotation is demonstrated starting with the elbow flexed to 90^0 and the shoulder in a neutral position. This motion ends with the shoulder fully internally rotated as seen from an anterior view.

External Rotation: With your arms at your sides, palms facing your body, bend your elbows 90 degrees. Keeping your elbows against your body swing your forearms away from your body. This is external rotation — also referred to as lateral rotation — and the normal range of motion for a healthy shoulder is 90 degrees as in Figure 2.7.

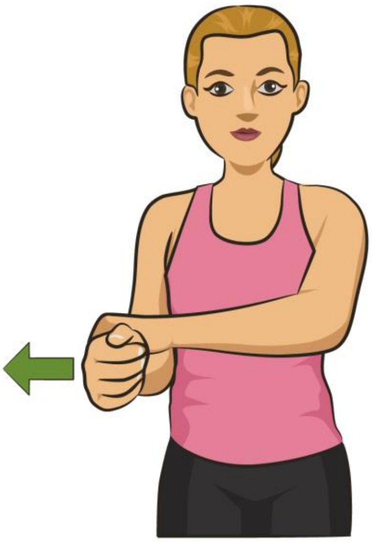


Figure 2.7: These muscles are small and generally can tolerate less weight than those that perform internal rotation. Start to holding on to a resisted band or pulley, rotate your upper arm away from your body without moving your elbow forward or backward. Again, imagine your arm is on a restitution.

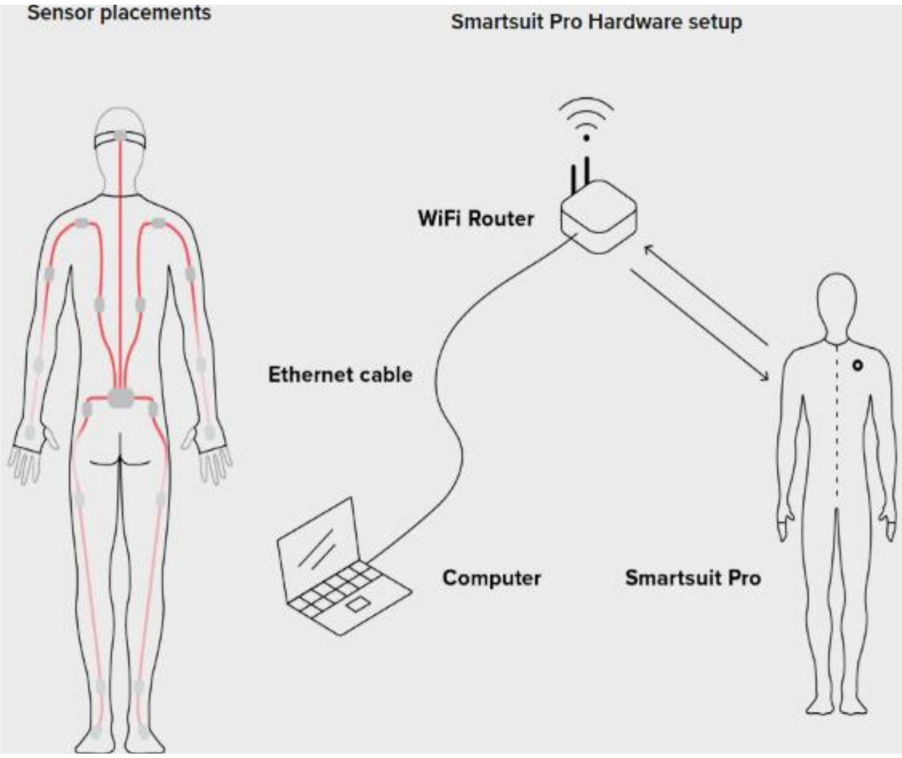


Figure 2.8: Configuration of sensors over the suit on the left hand side and hardware set up of Smartsuit Pro on the right hand side.

Wearable MOCAP System: Smartsuit Pro (Rokoko, Copenhagen, Denmark) consists of 19 sensors; 9 Degree of Freedom (DoF) inertial measurement units each connected with custom made cables, connecting all to a hub for wireless communication (Figure 2.8). Sensors are embedded in a suit, which is made of high performance, durable nylon based fabric. The suit has adjustable tightening straps to make it fit all body types. Seamlessly integrated tunnels protect all electronic parts, allowing movements without any restrictions. The hub consists of USB 2.0 Communication on board memory and a smart home button for one-person handling. WiFi is up to 100 m range. Communication is in real time with 100 frames per second. Smartsuit Pro uses Smartsuit Studio to observe the motion in real time in silico. Smartsuit Pro has a user friendly Graphical User Interface (GUI) to observe motion in real time. Rokoko Studio Software was operated on Windows platform. The battery allows for 6-hour operation time with 5000 mAh when longer motion scenarios are required.

Marker and Camera Based System: OptiTrack (LEYARD, Corvallis, USA) motion capture system consist of multiple cameras and custom-made marker sets (Figure 2.9). Use of OptiTrack is widespread in biomechanics after Vicon (Motion

Capture Systems, Oxford, UK) as a gold standard. Different from Smartsuit Pro, OptiTrack relies on marker sets. With OptiTrack, according to type of movement, specific marker sets and a number of cameras are used to capture the motion. OptiTrack is known for its high precision and processing capability. It can track markers down to submillimeter movements with repeatable accuracy and compute a skeleton model. Our OptiTrack System consists of six Flex 3 cameras (Figure 2.9), passive markers and Motive Software for motion data acquisition and recording purposes. OptiTrack has equal data sampling rate with 100 Hz .

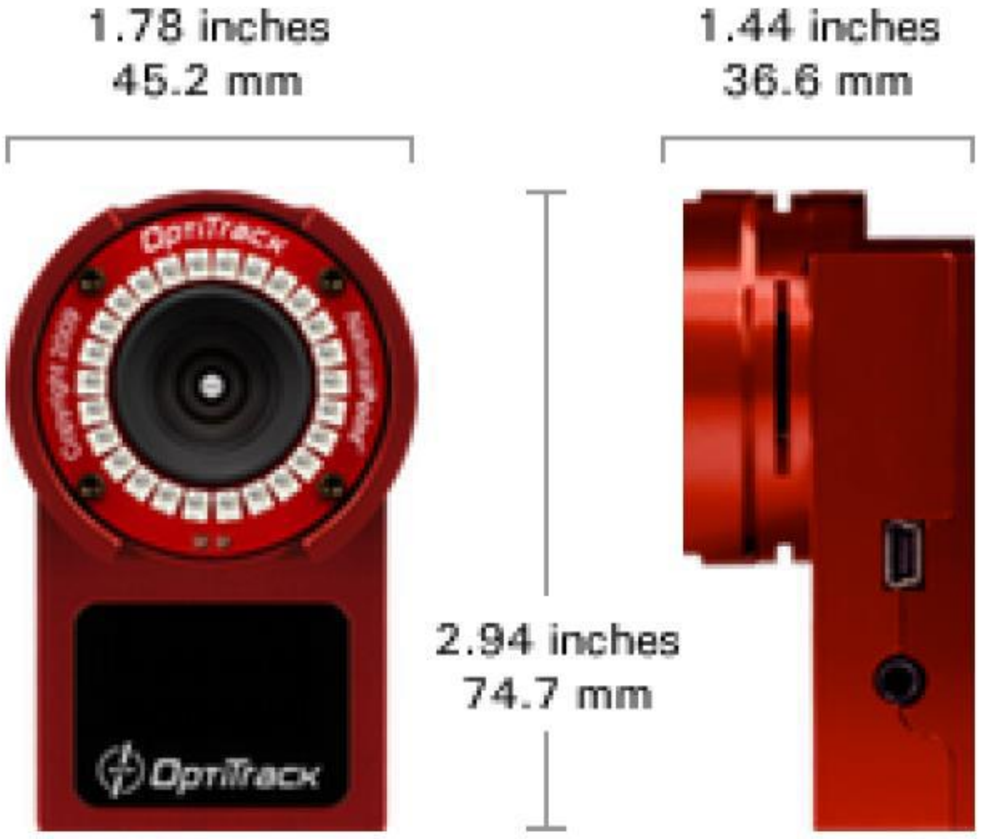


Figure 2.9: OptiTrack Flex 3 camera.

2.2 In Vivo Study

Ethics: The protocol was approved by the local Ethics Committee which of the Medical Faculty of Izmir Katip Celebi University. A written informed consent was obtained from each participant.

In vivo experiments volunteers have signed the consent form with 25 ± 7.2 age of 7 men and 7 women was conducted with 14 people. Volunteers are randomly chosen and the majority of them are students, their height is 172 ± 9.3 cm and their weight is 75 ± 14.2 kg.

In vivo study, the joint angles of interest for this experiment were bilaterally the shoulder (measured between the back and upper arm), the elbow (measured between the upper and lower arm) were calculated ROM flexion/extension in the frontal plane, abduction/adduction in the sagittal plane and internal/external rotation in horizontal plane. All movements were shown to volunteers and asked to repeat the movements (abduction, flexion and rotations) themselves 3 times.

The full system comprises 19 sensors 9 Degree of Freedom (DoF) inertial measurement sensors positioned on the body to capture the most information about the entire body's motion. Thus, each link (shoulder, arm, forearm, hand, thigh, shin and toe) has a sensor attached to it. Since the shoulders can move independently. Sensors are attached to the shoulder blades to capture their motion. The algorithm does not depend on the distance a sensor is placed from a joint (such as how far the forearm sensor is from the elbow), so the sensors are ideally placed where muscle contractions will not interfere with readings of gross body movements. Due to the aforementioned placement stipulations, the head would require an additional, seventeenth sensor. The system created in this study does not include this sensor, but the addition would be simple by following the same algorithm used.

The algorithm assumes an orientation of the sensor on the body in a way that makes it easy to perform the rotations and create the model of the body. Generally, the z-axis of each sensor is oriented away from the body, and except for the case of the shoulder, the x-axis is pointed in the direction of the body part (e.g. parallel with the femur for the thigh). The shoulder is oriented with the x-axis parallel with the hips to minimize the rotation of the sensor from the spine. As such, keeping the sensor as stationary as possible (not including full-body rotations) is ideal. Figure 2.10 displays the location and orientation of the sensors as well as joints and points of interest for creating the model of the body and calculating joint angles, with the global coordinate system shown between the feet.

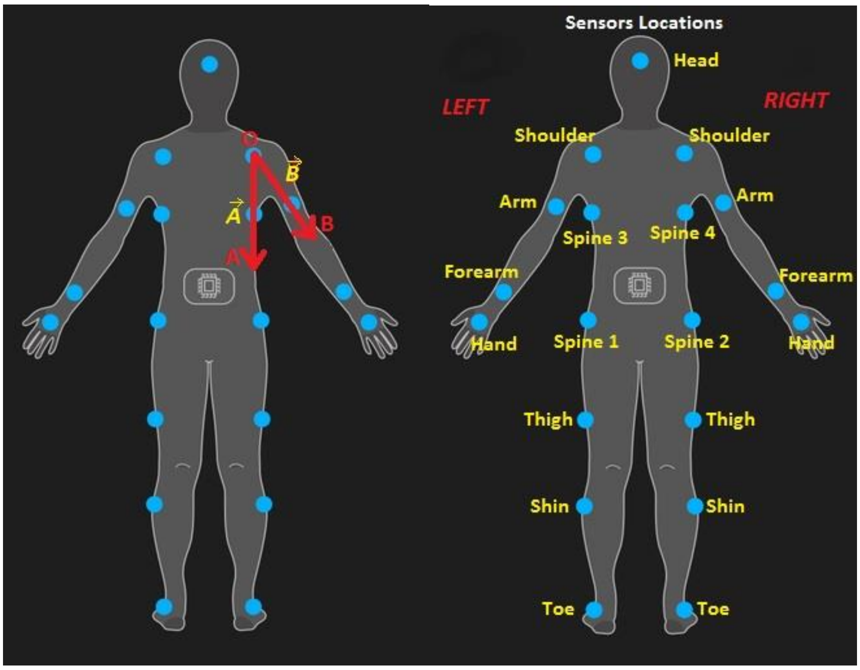


Figure 2.10: Diagram of position and orientation of the sensors on the body as well as joints and points of interest for joint angle calculation in vivo study.

In order to test the accuracy of the developed IMU-based MCS, a head to head comparison was done with both an optical MCS with a single subject. Both sensors were calibrated as needed by the system and then all of the sensors were atteched. The 19 IMU sensors were fitted to volunteer previously described. Three optical markers were used for the optical MCS after the calibration of systems.The positions of all the markers can be seen in Figure 2.11.

Figure 2.11: Marker positions for both Motion Capture Systems (MCSs) to import data from in vivo study.

2.3 Range of Motion Calculations: Data Processing

All data processing was done within MATLAB® (Math-Works. Inc.. Natick. MA. USA). Local marker coordinate systems for sensor on the shoulder and arm were defined such that each was aligned with its respective Rokoko and Optitrack coordinate systems:

$$\vec{A} = (x_2 - x_1, y_2 - y_1, z_2 - z_1) \tag{2.1}$$

$$\vec{\boldsymbol{B}} = (\boldsymbol{x_3} - \boldsymbol{x_1}, \boldsymbol{y_3} - \boldsymbol{y_1}, \boldsymbol{z_3} - \boldsymbol{z_1}) \tag{2.2}$$

$$\vec{A}x\vec{B} = AB \sin\alpha \tag{2.3}$$

$$\tan\alpha = \frac{\vec{A}x\vec{B}}{\vec{A}.\vec{B}} \tag{2.4}$$

$$\alpha = \tan^{-1}\frac{\vec{A}x\vec{B}}{\vec{A}.\vec{B}} \tag{2.5}$$

Range of motion were calculated between shoulder and arm sensors' local coordinate systems. Position data for each sensor were vectors on shoulder and arm coordinates. The range of motion was calculated according to above formulas that find the angle between shoulder and arm vectors. Finally, changes of angular temporally demonstrated with the help of following Matlab code.

Matlab Code

```
data = importdata('abduction.csv');     //Import motion data
spine = table2array(data(:.1:3);        //Get Spine Sensor data from all
data
shoulder = table2array(data(:.4:6);     //Get Shoulder Sensor data from all
data
hand = table2array(data(:.7:9);         //Get Hand Sensor data from all data
A=spine-shoulder;          // Create Vector A
B=hand-shoulder;           // Create Vector B
for i: length   //The length specifies the motion time (baud rate for each
data).
angle(i)=atan2d ( norm ( cross ( u(i. :). v(i. :))). dot ( u(i. :). v(i. :)
) );
end
plot(angle)          //Show angle
```

2.4 Data Analysis

2.4.1 RMSE

Root Mean Square Error (RMSE) measures how much error there is between two data sets. In other words, it compares a predicted value and an observed or known value.

Different than Mean Absolute Error (MAE), we use RMSE in a variety of applications when comparing two data sets which were given from Rokoko Smart suit and Optitrack *in vitro* and *in vivo* studies.

Root mean square error takes the difference of both system values. You can swap the order of subtraction because the next step is to take the square of the difference. This is because the square of a negative value will always be a positive value.

But just make sure that you keep the same order throughout. After that, divide the sum of all values by the number of observations. Finally, we get an RMSE value which is calculated by

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{n}} \qquad \textbf{(2.6)}$$

2.4.2 Bland-Altman Analysis

Bland and Altman introduced the Bland-Altman (B&A) plot to describe agreement between two quantitative measurements by constructing limits of agreement. These statistical limits are calculated by using the mean and the standard deviation (s) of the differences between two measurements. To check the assumptions of normality of differences and other characteristics, they used a graphical approach.

The resulting graph is a scatter plot XY, in which the Y axis shows the difference between the two paired measurements (A-B) and the X axis represents the average of these measures ((A+B)/2). In other words, the difference of the two paired measurements is plotted against the mean of the two measurements. B&A recommended that 95% of the data points should lie within $\pm\ 2s$ of the mean difference. This is the most common way to plot the B&A method, but it is also possible to plot the differences as percentages or ratios, and one can use the first method or the second one, instead of the mean of both methods.

The bias is computed as the value determined by one method minus the value determined by the other method. If one method is sometimes higher, and sometimes the other method is higher, the average of the differences will be close to zero. If it is not close to zero, this indicates that the two prove methods are systematically producing different results.

3. RESULTS

3.1 In Vitro Result

The in-vitro result of this thesis kinematic data are received 3 samples by MOCAP systems to calculate the ROM of shoulder flexion with the help of Matlab. Sample-1 is shown below in Figure 3.1.

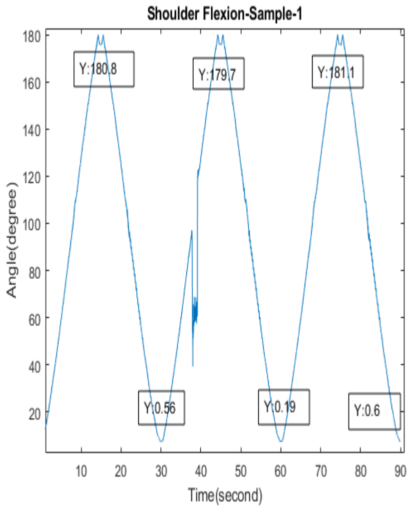
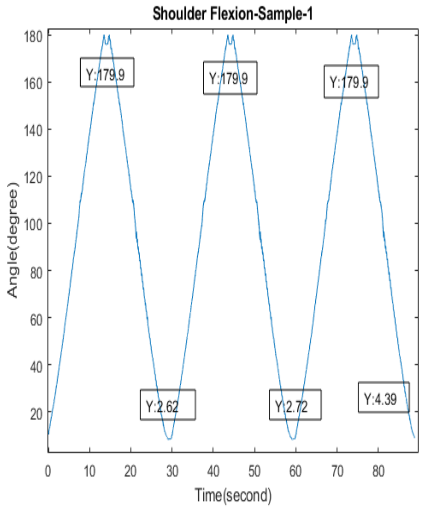
EXPERIMENT / MOCAP SYSTEMS	**ROKOKO RESULTS**	**OPTITRACK RESULTS**
SHOULDER FLEXION		

Figure 3.12: The in vitro result of ROM of shoulder flexion were compared between ROKOKO and OPTITRACK shown as an example.

Shoulder flexion was performed 3 times in each sample. In this study each sample have 3 ROM and a total of 9 ROM were obtained. The results of ROM are shown below in Table 3.1.

According to result of ROM in vitro for shoulder flexion RMSE were 0.66 and 0.96 degrees respectively for Rokoko and OptiTrack. Lower values of RMSE indicate better fit.

Table 3.1: The in vitro MOCAP systems all samples result of ROM in shoulder flexion.

EXPERIMENT	ROKOKO RESULTS	OPTITRACK RESULTS	EXPERIMENTAL RESULTS
SAMPLE 1-1	180.24	177.28	180
SAMPLE 1-2	179.51	177.18	180
SAMPLE 1-3	180.5	175.51	180
SAMPLE 2-1	179.98	178.54	180
SAMPLE 2-2	180.28	178.44	180
SAMPLE 2-3	180.02	178.42	180
SAMPLE 3-1	180.52	178.44	180
SAMPLE 3-2	181.09	178.43	180
SAMPLE 3-3	180.82	180.27	180

The Bland-Altman plot simply quantified the difference between measurements. The data points can be restricted using +1.96 standard deviation (SD) to demonstrate a 95% confidence interval of distributed data. For our dataset, the mean difference was found as 3.27 with an SD of 1.749. The upper limit can be calculated using **Mean + 1.96 x SD** **(3.27 + 1.96x1.749=6.698)** and lower limit can be calculated using **Mean - 1.96 x SD (3.27 - 1.96x1.749= -0.158)**. The appropriate statement used in manuscript can be seen below Bland-Altman Figure 3.2 of MOCAP systems. The scatterplot can be evaluated according to the scatter dispersion. As a quantifiable measure, mean bias and limits of the agreement give information about the utility of the Rokoko system. Regarding our data set, those two MOCAP systems can be used interchangeably.

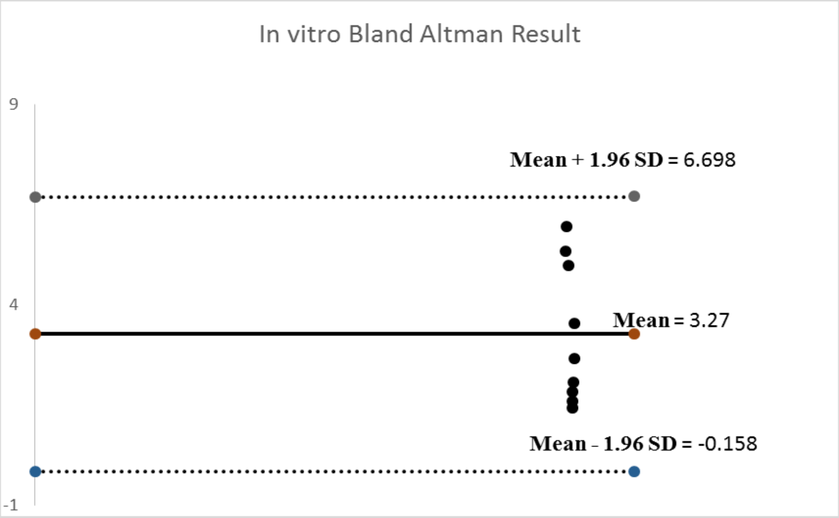


Figure 3.2: In vitro Bland-Altman result of shoulder flexion from Rokoko and Optitrack.

3.2 In Vivo Results

3.2.1 In Vivo Results in Frontal Plane

The in-vivo result of this thesis, kinematic data are received from 14 volunteers by MOCAP systems were calculated the ROM of 9 movements in 3 different planes with the help of Matlab. Abduction and hair combing movements in the frontal plane were repeated 3 times and performed by each volunteer. Abduction result of Volunteer-1 and hair combing result of Volunteer-9 are shown below in Figure 3.3.

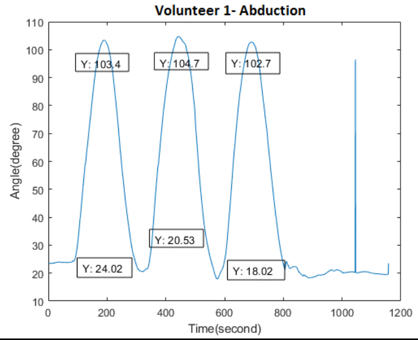
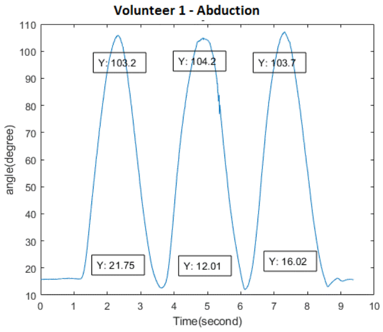
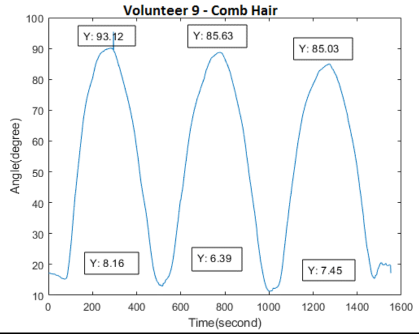
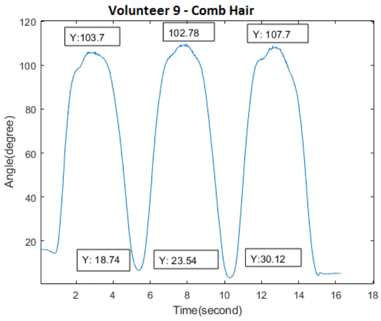
EXPERIMENT / MOCAP SYSTEMS	**ROKOKO RESULT**	**OPTITRACK RESULT**
ABDUCTION		
HAIR COMBING		

Figure 3.3: The comparison of in vivo result of ROM of abduction and hair combing between ROKOKO and OPTITRACK be shown as an example.

In order to compare the Rokoko and Optitrack systems in abduction and hair combing movements in the frontal plane, 84 data were obtained from each system. The results of ROM are shown below in Table 3.2.

Table 3.2: The in vivo MOCAP systems result of ROM in abduction and hair combing in frontal plane.

VOLUNTEERS/ MOVEMENTS		VOLUNTEER-1	VOLUNTEER-2	VOLUNTEER-3	VOLUNTEER-4	VOLUNTEER-5	VOLUNTEER-6	VOLUNTEER-7	VOLUNNTER-8	VOLUNTEER-9	VOLUNTEER-10	VOLUNTEER-11	VOLUNTEER-12	VOLUNTEER-13	VOLUNTEER-14
ROKOKO RESULTS	ABDUCTION SAMPLE-1	85.67	93.61	93.99	90.95	83.05	79.38	93.61	79.38	92.55	84.78	79.38	93.61	79.38	90.95
	ABDUCTION SAMPLE-2	82.47	93.15	93.05	86.92	76.39	84.17	93.15	84.17	87.45	77.2	84.17	93.15	84.17	86.92
	ABDUCTION SAMPLE-3	84.13	94.83	92.45	82.84	76.42	84.68	94.83	84.68	84.88	75.89	84.68	94.83	84.68	82.84
	COMB HAIR SAMPLE-1	56.12	88.01	93.99	113.26	103.08	84.96	97.15	76.24	109.81	103.08	84.96	95.45	76.24	113.26
	COMB HAIR SAMPLE-2	51.29	97.15	93.05	95.18	86.23	79.24	97.47	83.82	96.18	98.36	84.24	95.47	83.82	95.18
	COMB HAIR SAMPLE-3	47.32	97.47	92.45	94.13	85.75	77.58	88.01	90.35	95.08	87.45	87.58	88.01	90.35	94.13
OPTITRACK RESULTS	ABDUCTION SAMPLE-1	83.69	96.33	97.53	90.95	85.45	88.19	93.85	81.45	91.87	85.45	82.19	93.85	81.45	90.95
	ABDUCTION SAMPLE-2	82.98	93.64	96.13	89.21	77.08	85.97	97.19	92.19	86.78	77.08	85.97	97.19	92.19	89.21
	ABDUCTION SAMPLE-3	85.23	96.99	95.19	85.78	75.63	86.33	98.31	85.55	84.78	75.63	86.33	98.31	87.68	85.78
	COMB HAIR SAMPLE-1	64.25	92.3	99.58	116.34	106.62	91.55	93.96	85.39	113.25	106.62	91.55	93.96	85.39	116.34
	COMB HAIR SAMPLE-2	64.07	97.2	98.45	99.44	101.23	89.79	93.94	83.21	97.25	101.23	89.79	93.94	83.21	99.44
	COMB HAIR SAMPLE-3	63.25	97.46	94.8	99.69	96.56	90.88	91.61	85.03	96.42	92.3	90.88	91.61	85.03	99.69

The Bland-Altman graph simply measured the difference between measurements. Data scores can be limited using +1.96 standard deviation (SD) to indicate the 95% confidence interval of the distributed data. For our dataset, the mean difference was found as -2.001 with an SD of 2.29. The upper limit can be calculated using **Mean + 1.96 x SD (-2.001 + 1.96x2.29=2.5027**) and lower limit can be calculated using **Mean - 1.96 x SD (-2.001 - 1.96x2.29= -6.5051**). The appropriate statement used in manuscript can be seen below Bland-Altman Figure 3.4 of MOCAP systems. The scatterplot can be evaluated according to the scatter dispersion. As a quantifiable measure, mean bias and limits of the agreement give information about the utility of the Rokoko system. Regarding our data set, those two MOCAP systems can be used interchangeably.

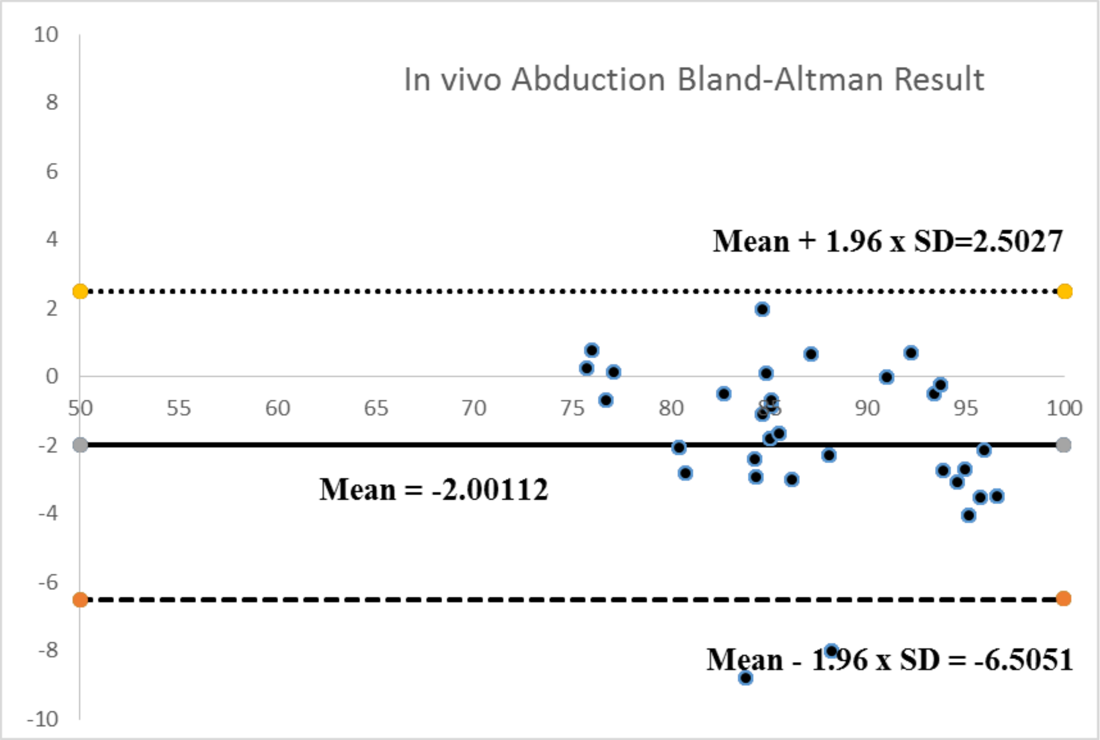


Figure 3.4: In vivo Bland- Altman result of abduction in frontal plane from Rokoko and Optitrack.

The appropriate statement used in manuscript can be seen below Bland-Altman Figure 3.4 of MOCAP systems. The scatterplot can be evaluated according to the scatter dispersion. As a quantifiable measure, mean bias and limits of the agreement give information about the utility of the Rokoko system. Regarding our data set, those two MOCAP systems can be used interchangeably. The upper limit is less than 5% of the data received when Bland-Altman exceeds two points, so the graph shows that Rococo and Optitrack indicate important results in hair combing movement.

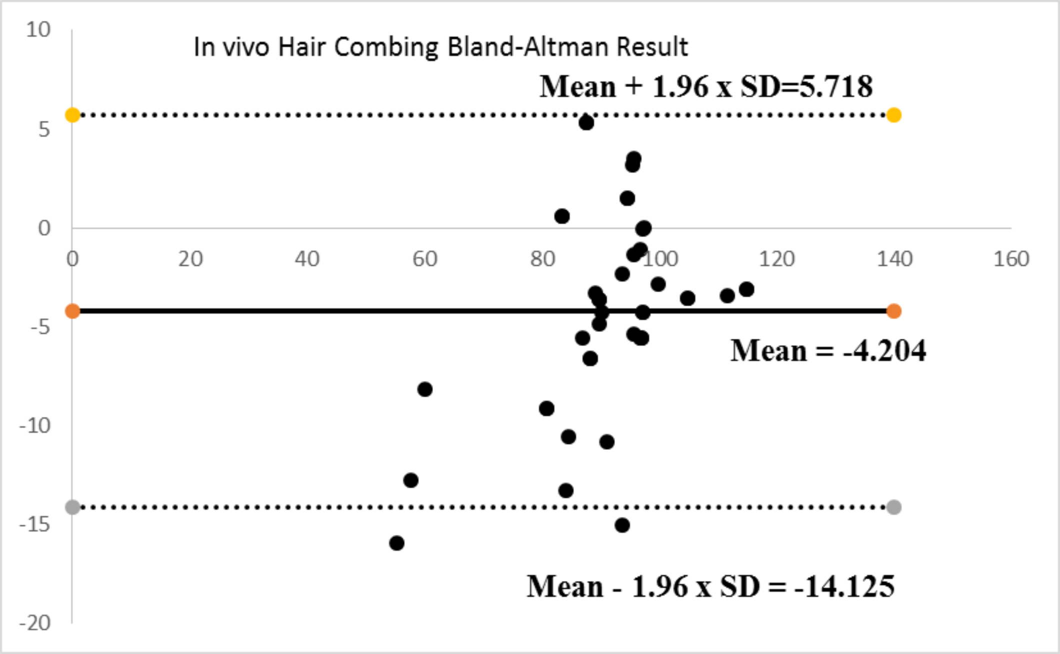


Figure 3.5: In vivo Bland- Altman result of hair combing in frontal plane from Rokoko and Optitrack.

According to result of ROM in vivo for abduction movements in frontal plane averagely were calculated as 9.65 and 8.8 degrees respectively. Lower values of RMSE indicate better fit for Rokoko and Optitrack. The upper limit is less than 5% of the data received when Bland-Altman exceeds two points, so the graph shows that ROKOKO and OPTITRACK indicate acceptable results in hair combing movement in Figure 3.5.

3.2.2 In Vivo Results in Sagittal Plane

Shoulder flexion, Elbow flexion and wear glasses movements in the sagittal plane were repeated 3 times and performed by each volunteer. Shoulder flexion result of Volunteer-8 and elbow flexion result of Volunteer-3 and wear glasses result of Volunteer-2 are shown below in Figure 3.6.

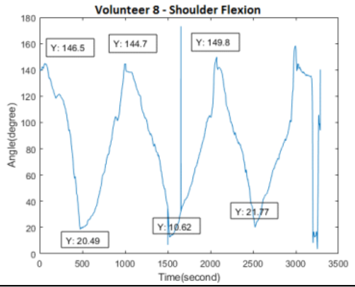
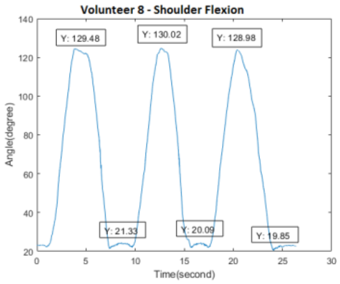
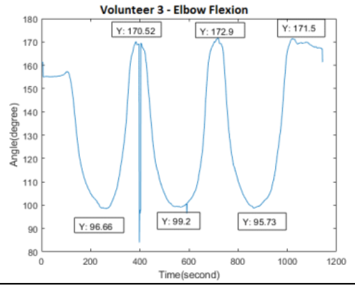
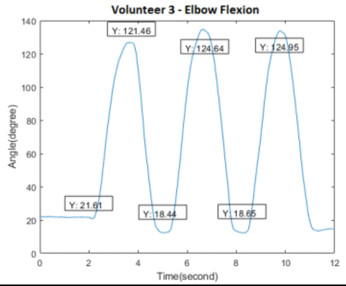
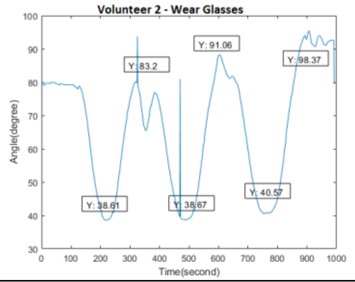
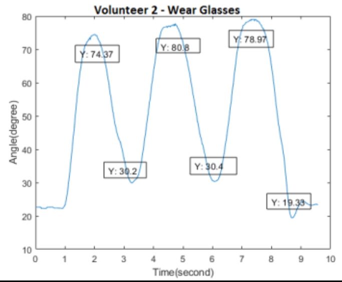
EXPERIMENT/ MOCAP SYSTEMS	**ROKOKO RESULT**	**OPTITRACK RESULT**
SHOULDER FLEXION		
ELBOW FLEXION		
WEAR GLASSES		

Figure 3.6: The comparison of in vivo result of ROM of shoulder flexion, elbow flexion and wear glasses between ROKOKO and OPTITRACK shown as an example.

In order to compare the Rokoko and Optitrack systems in shoulder flexion, elbow flexion and wear glasses movements in the sagittal plane. 126 data were obtained from each system. The results of ROM are shown below in Table 3.3.

Table 3.3: The in vivo MOCAP systems result of ROM in shoulder flexion, elbow sflexion and wear glasses in sagittal plane.

VOLUNTEERS/ MOVEMENTS		VOLUNTEER-1	VOLUNTEER-2	VOLUNTEER-3	VOLUNTEER-4	VOLUNTEER-5	VOLUNTEER-6	VOLUNTEER-7	VOLUNNTER-8	VOLUNTEER-9	VOLUNTEER-10	VOLUNTEER-11	VOLUNTEER-12	VOLUNTEER-13	VOLUNTEER-14
ROKOKO RESULTS	SHOULDER FLEXION SAMPLE-1	129.7	127.86	76.24	143.65	126.01	155.36	127.86	121.05	143.65	126.01	155.36	127.86	129.05	143.65
	SHOULDER FLEXION SAMPLE-2	137.72	127.45	83.82	140.46	134.08	156.53	127.45	122.09	147.62	132.6	156.53	127.45	132.09	140.46
	SHOULDER FLEXION SAMPLE-3	133.09	127.9	90.35	137.24	128.03	153.32	127.9	120.84	138.89	128.03	143.2	127.9	130.89	137.24
	ELBOW FLEXION SAMPLE-1	124.89	135.13	123.28	73.86	159.04	124.89	145.13	138.45	82.46	139.05	124.89	135.11	138.45	83.86
	ELBOW FLEXION SAMPLE-2	132.53	139.92	123.97	74.7	158.33	132.53	139.92	134.52	77.99	138.48	132.53	139.92	134.52	94.7
	ELBOW FLEXION SAMPLE-3	154.05	138.56	124.98	75.77	129.25	153.85	138.56	130.28	79.42	129.25	133.85	138.56	130.28	97.77
	WEAR GLASSES SAMPLE-1	44.58	57.49	44.59	63.3	56.9	44.58	57.49	63.84	61.84	56.9	44.58	57.49	63.84	62.3
	WEAR GLASSES SAMPLE-2	49.29	63.33	52.39	60	56.55	49.29	63.33	64.83	59.79	56.55	49.29	62.33	64.83	59.45
	WEAR GLASSES SAMPLE-3	52.5	58.99	57.8	67.41	56.11	52.5	58.99	70.69	67.41	56.11	52.5	58.99	70.69	67.41
OPTITRACK RESULTS	SHOULDER FLEXION SAMPLE-1	116.9	111.78	77.44	152.43	108.15	145.4	125.94	139.68	152.43	128.15	145.4	125.94	137.5	152.43
	SHOULDER FLEXION SAMPLE-2	121.5	110.8	85	150.87	109.93	151.5	127.97	136.17	150.87	130.12	151.5	127.97	136.17	150.87
	SHOULDER FLEXION SAMPLE-3	129.2	114.85	90.89	143.3	109.13	138.6	129.26	136.94	143.3	129.13	138.6	129.26	136.94	143.3
	ELBOW FLEXION SAMPLE-1	124.57	135.6	111.6	99.85	134.4	123.91	131.6	130.82	97.38	134.4	123.91	131.6	130.82	99.85
	ELBOW FLEXION SAMPLE-2	132.48	136.5	112.4	100.2	134.7	128.33	130.7	132.55	98.45	134.7	128.33	135.7	132.55	100.2
	ELBOW FLEXION SAMPLE-3	134.78	136.1	114.1	101.3	123.3	126.56	130.4	130.98	95.41	123.3	126.56	134.4	130.98	101.3
	WEAR GLASSES SAMPLE-1	46.41	48.86	44.17	63.3	61.46	39.6	57.79	64.98	62.24	61.46	39.6	57.79	64.98	63.12
	WEAR GLASSES SAMPLE-2	47.66	51.55	50.4	60.45	63.08	41.09	58.11	64.56	60.45	63.08	41.09	58.11	64.56	60.15
	WEAR GLASSES SAMPLE-3	47.76	51.54	59.64	67.34	65.29	35.02	54.65	70.71	67.34	65.29	45.02	54.65	70.71	67.34

The Bland-Altman plot simply quantified the difference between measurements.The data points can be restricted using +1.96 standard deviation (SD) to demonstrate a 95% confidence interval of distributed data. For our dataset, the mean difference was found as -0.215 with an SD of 8.78. The upper limit can be calculated using **Mean + 1.96 x SD (-0.215 + 1.96x8.78=17.0013**) and lower limit can be calculated using **Mean - 1.96 x SD (-0.215 - 1.96x8.78= -17.4313**). The appropriate statement used in manuscript can be seen below Bland-Altman Figure 3.7 of MOCAP systems. The scatterplot can be evaluated according to the scatter dispersion. As a quantifiable measure, mean bias and limits of the agreement give information about the utility of the Rokoko system. Regarding our data set, those two MOCAP systems can be used interchangeably.

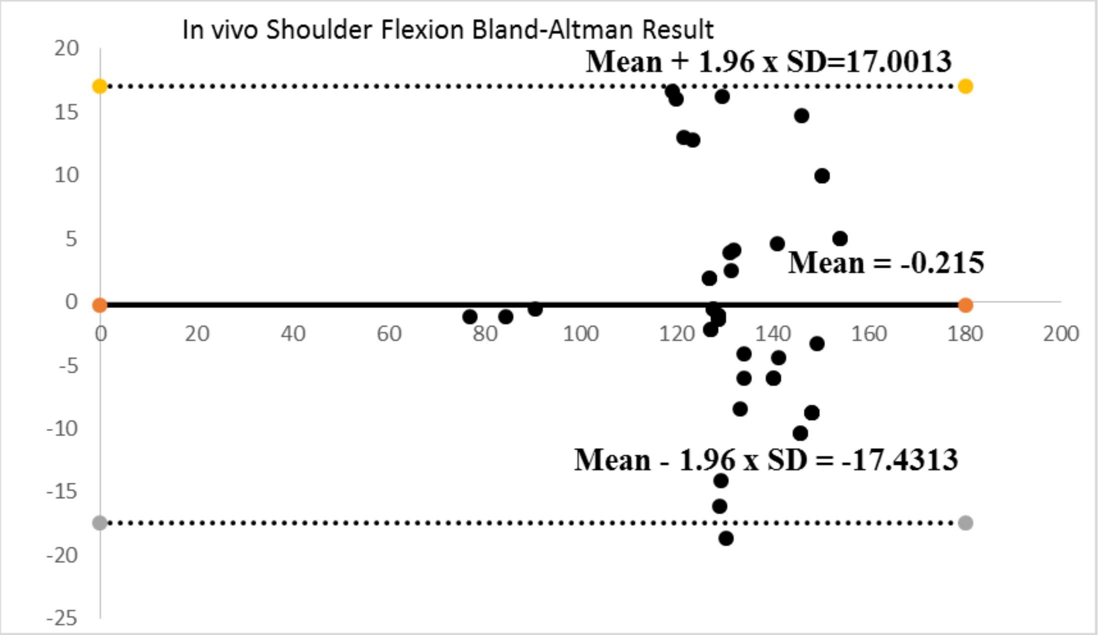


Figure 3.713: In vivo Bland- Altman result of shoulder flexion in sagittal plane from Rokoko and Optitrack.

The appropriate statement used in manuscript can be seen below Bland-Altman Figure 3.8 of MOCAP systems. The scatterplot can be evaluated according to the scatter dispersion. As a quantifiable measure of wear glasses mean bias and limits of the agreement give information about the utility of the Rokoko system. The upper limit is less than 5% of the data received when Bland-Altman exceeds one point, so the graph shows that Rococo and Optitrack indicate acceptable results in wear glasses movement.

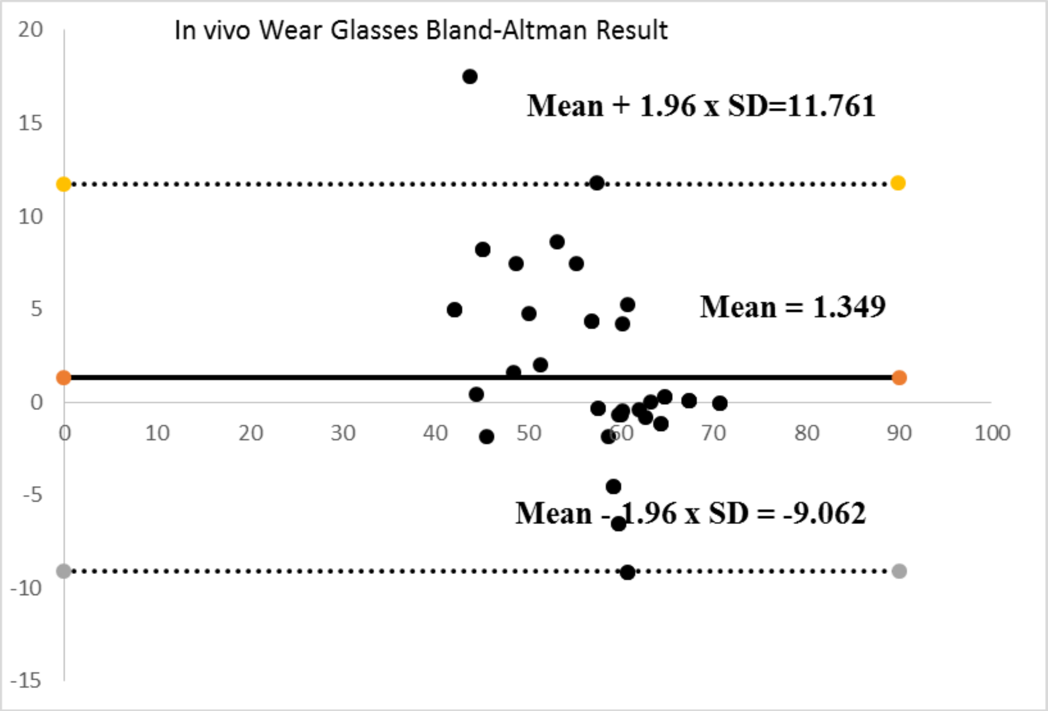


Figure 3.8: In vivo Bland- Altman result of wear glasses in sagittal plane from Rokoko and Optitrack.

The appropriate statement used in manuscript can be show below Bland-Altman Figure 3.9 of mocap systems. The scatterplot can be evaluated according to the scatter dispersion.As a quantifiable measure of elbow flexion mean bias and limits of the agreement give information about the utility of the Rokoko system. Regarding our data set. those two mocap systems can be used interchangeably.

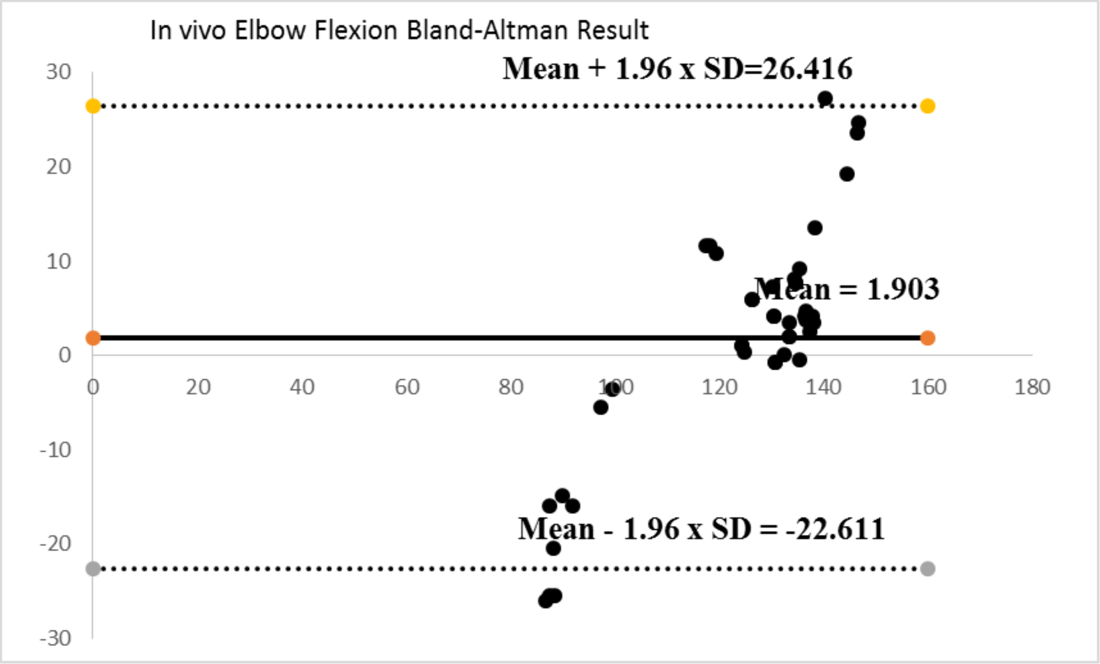


Figure 3.9: In vivo Bland- Altman result of elbow flexion in sagittal plane from Rokoko and Optitrack.

The ROM was calculated as 15.8 and 13.44 on average between the Rococo and Optitrack for shoulder and elbow flexion movements in the sagittal plane in vivo. Low RMSE values indicate that it is more suitable for Rococo and Optitrack.

3.2.3 In Vivo Results in Horizontal Plane

Internal rotation, external rotation, tooth brushing and fugl meyer movements in the horizontal plane were repeated 3 times and performed by each volunteer. Internal rotation result of Volunteer-10 and external rotation result of Volunteer-6 and tooth brushing result of Volunteer-12 and Fugl meyer result of Volunteer-11 are shown below in Figure 3.10.

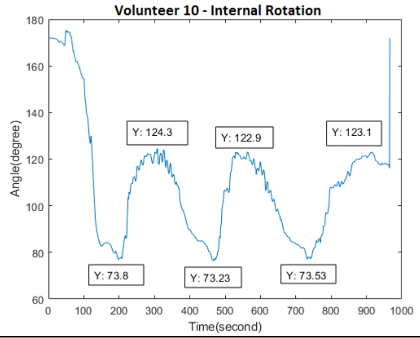
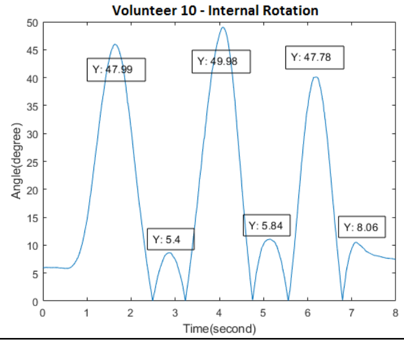
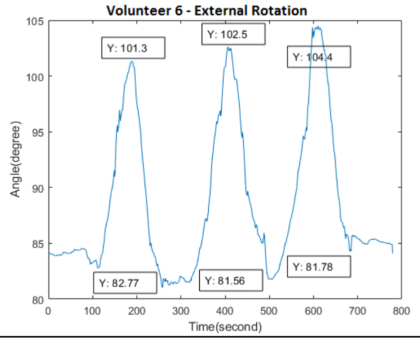
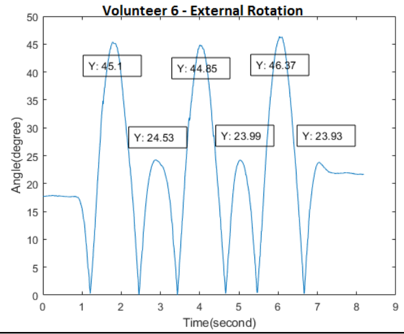
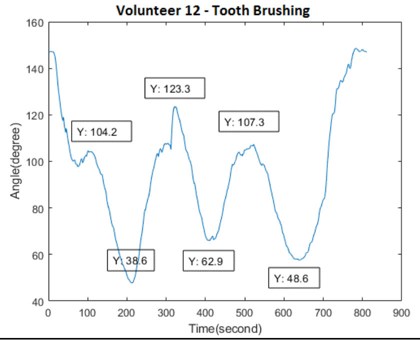
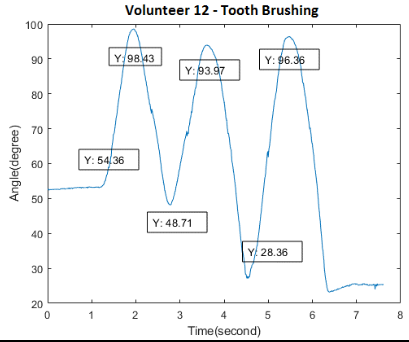
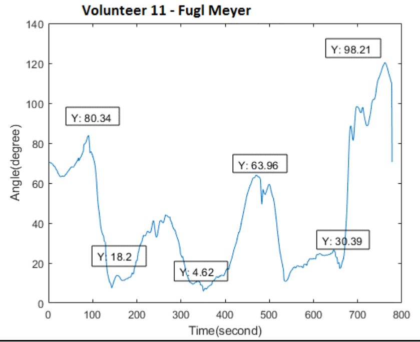
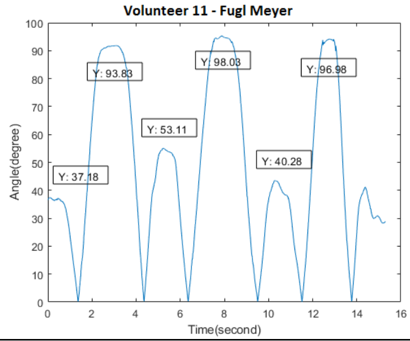
EXPERIMENT/ MOCAP SYSTEMS	ROKOKO RESULT	OPTITRACK RESULT
INTERNAL ROTATION		
EXTERNAL ROTATION		
TOOTH BRUSHING		
FUGL MEYER		

Figure 3.10: The comparison of in vivo result of ROM of internal rotation, external rotation, toothbrushing and fugl meyer between ROKOKO and OPTITRACK are shown as an example.

In order to compare the Rokoko and Optitrak systems in internal rotation, external rotation, tooth brushing and fugl meyer movements in the horizontal plane. 168 data were obtained from each system. The results of ROM are shown below in Table 3.4.

Table 3.4: The in vivo MOCAP systems result of ROM in internal rotation, external rotation, tooth brushing and fugl meyer in horizontal plane.

VOLUNTEERS/ MOVEMENTS		VOLUNTEER-1	VOLUNTEER-2	VOLUNTEER-3	VOLUNTEER-4	VOLUNTEER-5	VOLUNTEER-6	VOLUNTEER-7	VOLUNNTER-8	VOLUNTEER-9	VOLUNTEER-10	VOLUNTEER-11	VOLUNTEER-12	VOLUNTEER-13	VOLUNTEER-14
ROKOKO RESULTS	INTERNAL ROTATION SAMPLE-1	85.88	62.58	92.6	74.05	95.39	50.5	72.92	65.75	74.05	95.39	50.5	67.92	65.75	84.07
	INTERNAL ROTATION SAMPLE-2	77.72	64.59	88.38	85.62	92.83	49.67	54.42	58.88	85.62	92.83	49.67	54.42	58.88	85.62
	INTERNAL ROTATION SAMPLE-3	76.68	67.85	89.15	70.35	94.62	49.57	53.64	53.64	82.95	92.14	49.57	53.64	53.64	70.35
	EXTERNAL ROTATION SAMPLE-1	58.43	18.53	45.1	40.77	38.7	43.84	23.68	35.64	40.77	38.7	43.84	43.68	35.64	40.77
	EXTERNAL ROTATION SAMPLE-2	53.91	20.94	44.3	36.47	37.7	46	25.64	28.89	36.47	37.7	46	35.64	28.89	36.47
	EXTERNAL ROTATION SAMPLE-3	59.69	22.62	44.2	42.57	36.02	59.76	35.82	38.46	42.57	36.02	49.76	35.82	38.46	42.57
	TOOTH BRUSHING SAMPLE-1	84.32	78.4	72.94	65.6	31.52	58.71	28.17	35.78	65.6	45.8	48.71	28.17	35.78	65.6
	TOOTH BRUSHING SAMPLE-2	85.12	83.44	68.15	60.4	36.82	59.24	61.44	48.38	60.4	45.27	49.24	61.44	48.38	60.4
	TOOTH BRUSHING SAMPLE-3	87.42	76.48	58.2	53.2	37.64	34.17	34.24	47.12	58.7	47.64	44.17	34.24	47.12	63.42
	FUGL MEYER SAMPLE-1	79.14	53.5	76.34	107	99.14	67.21	63.64	63.64	105.48	89.14	67.21	63.64	63.64	107
	FUGL MEYER SAMPLE-2	76.48	48.1	62.1	82.6	71.48	74.1	59.34	59.34	82.6	71.48	74.1	59.34	59.34	82.6
	FUGL MEYER SAMPLE-3	78.39	51.6	71.54	103.2	98.39	75.9	67.82	67.82	103.2	78.39	75.9	67.82	67.82	103.2
OPTITRACK RESULTS	INTERNAL ROTATION SAMPLE-1	86.24	57.01	82.25	74.32	79.95	32.59	52.77	55.98	74.32	85.95	42.59	62.77	55.98	74.32
	INTERNAL ROTATION SAMPLE-2	76.75	57.94	81.45	84.28	84.6	34.14	47.24	52.95	84.28	88.6	44.14	49.42	52.95	84.28
	INTERNAL ROTATION SAMPLE-3	75.99	60.96	83.01	80.62	84.37	39.72	47.98	48.86	80.62	84.37	39.72	47.98	48.86	80.62
	EXTERNAL ROTATION SAMPLE-1	54.22	20.57	46.86	49.03	37.87	49.85	50.75	40.32	49.03	37.87	49.85	50.75	40.32	49.03
	EXTERNAL ROTATION SAMPLE-2	52.62	20.86	46.01	45.25	37.08	49.82	43.18	38.12	45.25	37.08	49.82	43.18	38.12	45.25
	EXTERNAL ROTATION SAMPLE-3	53.09	22.44	45.92	50.11	34.97	40.59	41.85	41.85	50.11	34.97	40.59	41.85	41.85	50.11
	TOOTH BRUSHING SAMPLE-1	83.61	75.61	75.64	71.71	56.38	44.07	36.46	36.46	71.71	52.42	44.07	36.46	36.46	71.71
	TOOTH BRUSHING SAMPLE-2	85.95	85.62	70.74	70.73	60.11	45.26	65.89	55.15	70.73	50.11	45.26	65.89	55.15	70.73
	TOOTH BRUSHING SAMPLE-3	87.6	73.3	72.26	66.66	66.92	58	38.82	38.82	66.66	56.92	58	38.82	38.82	66.66
	FUGL MEYER SAMPLE-1	78.6	42.83	76.11	106.8	78.75	69.75	71.65	71.65	104.2	88.75	69.75	71.65	71.65	106.8
	FUGL MEYER SAMPLE-2	76.65	42.01	63.37	90.78	77.44	76.86	51.92	51.92	90.78	77.44	76.86	51.92	51.92	90.78
	FUGL MEYER SAMPLE-3	75.85	43.89	74.86	103.53	75.65	74.2	59.75	59.75	103.53	75.65	74.2	59.75	59.75	103.53

The Bland-Altman plot simply quantified the difference between measurements. The data points can be restricted using +1.96 standard deviation (SD) to demonstrate a 95% confidence interval of distributed data. For our dataset, the mean difference was found as 5.9655 with an SD of 5.94. The upper limit can be calculated using **Mean + 1.96 x SD (5.9655 + 1.96x5.94=17.6104**) and lower limit can be calculated using **Mean - 1.96 x SD (5.9655 - 1.96x5.94= -5.6794**). The appropriate statement used in manuscript can be show below Bland-Altman Figure 3.11 of MOCAP systems. The scatterplot can be evaluated according to the scatter dispersion. As a quantifiable measure, mean bias and limits of the agreement give information about the utility of the Rokoko system. Regarding our data set, those two MOCAP systems can be used interchangeably.

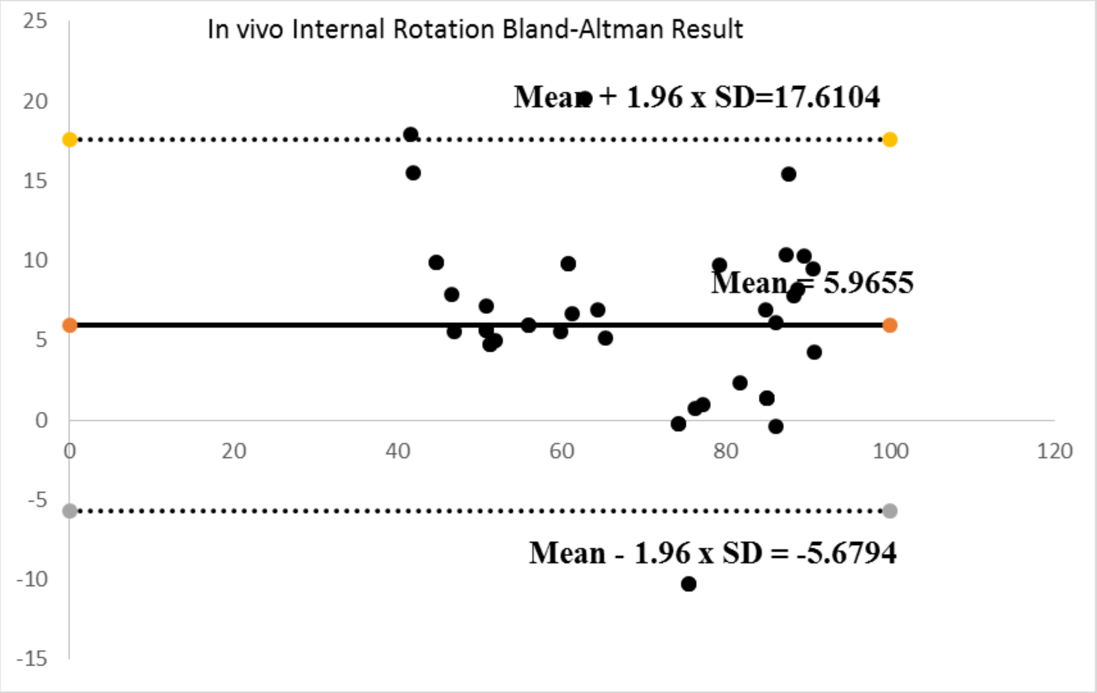


Figure 3.11: In vivo Bland- Altman result of internal rotation in horizontal plane from Rokoko and Optitrack.

The appropriate statement used in manuscript can be seen below Bland-Altman Figure 3.12 of MOCAP systems. The scatterplot can be evaluated according to the scatter dispersion. As a quantifiable measure external rotation of mean bias and limits of the agreement give information about the utility of the Rokoko system. The upper and lower limit is less than 5% of the data received when Bland-Altman exceeds two points, so the graph shows that Rococo and Optitrack indicate important results in external rotation movement.

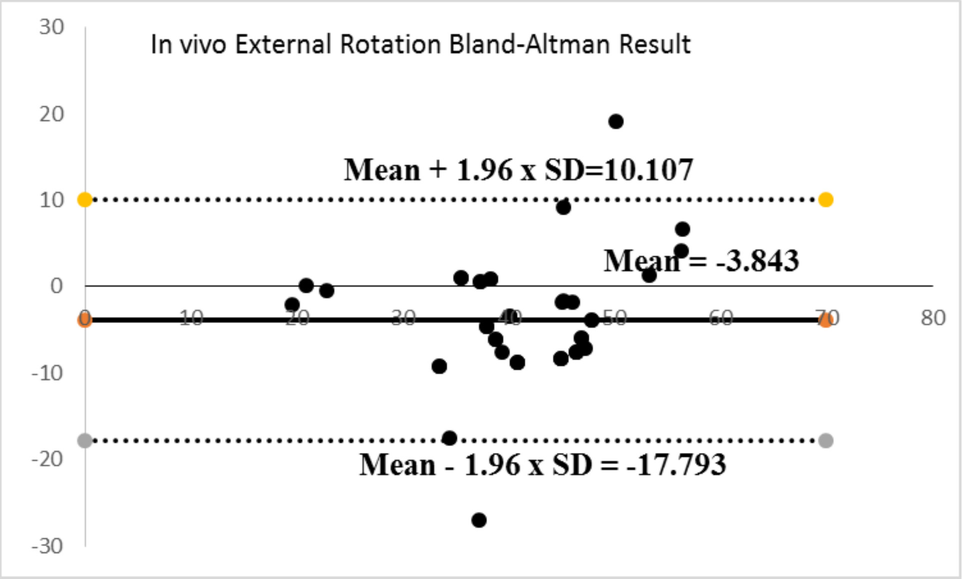


Figure 14.12: In vivo Bland- Altman result of external rotation in horizontal plane from Rokoko and Optitrack.

The appropriate statement used in manuscript can be seen below Bland-Altman Figure 3.13 of MOCAP systems. The scatterplot can be evaluated according to the scatter dispersion. As a quantifiable measure tooth brushing of mean bias and limits of the agreement give information about the utility of the Rokoko system. Exceeds the upper limit Bland-Altman for four points is more than 5% of the data 42 received graphic indicates that Rokoko and Optitrack results have inter-plane motion disturbances when tooth brushing.

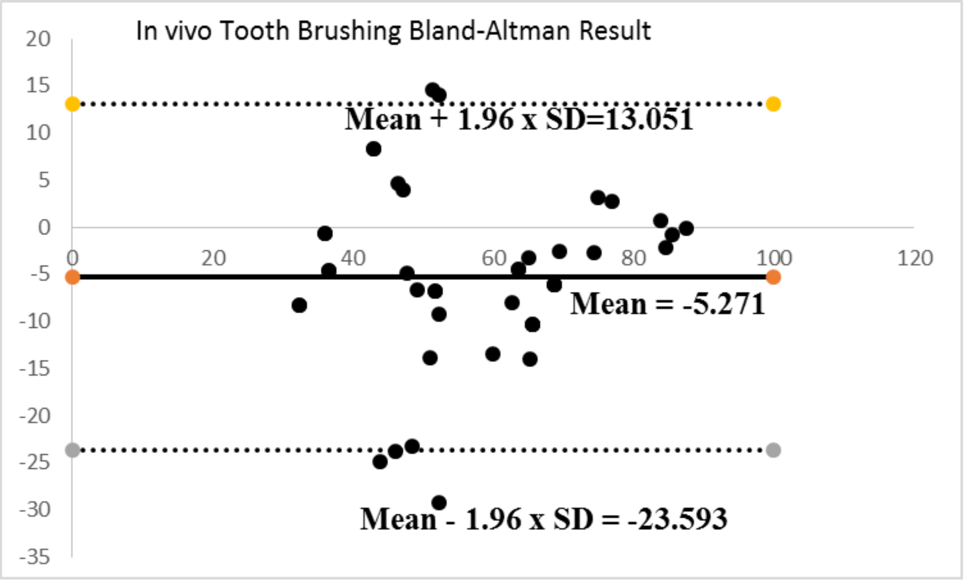


Figure 3.13: In vivo Bland- Altman result of tooth brushing in horizontal plane from Rokoko and Optitrack.

The appropriate statement used in manuscript can be seen below Bland-Altman Figure 3.14 of MOCAP systems. The scatterplot can be evaluated according to the scatter dispersion. As a quantifiable measure fugl meyer of mean bias and limits of the agreement give information about the utility of the Rokoko system.

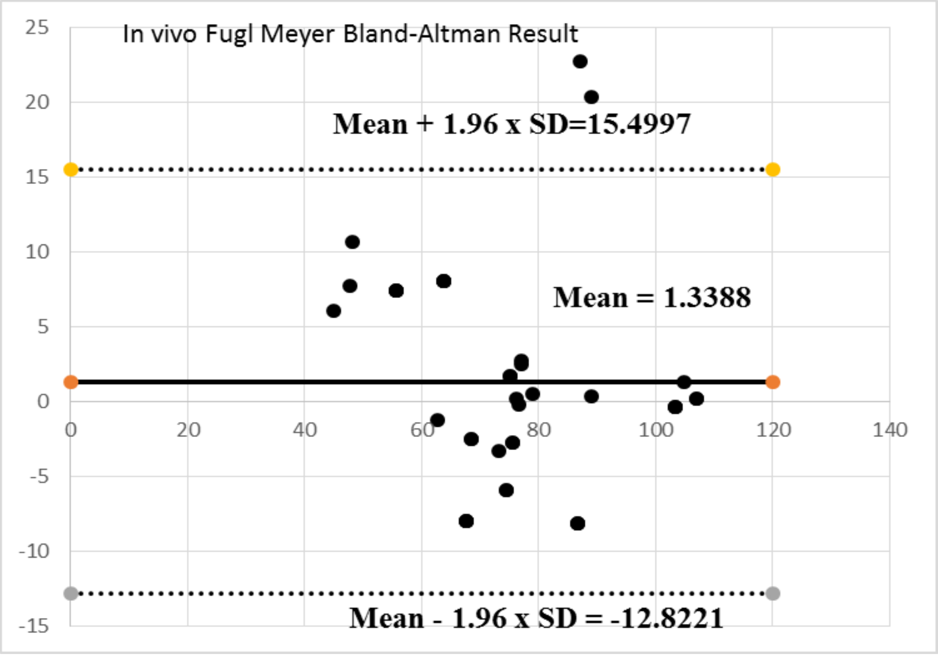


Figure 3.14: In vivo Bland- Altman result of fugl meyer in horizontal plane from Rokoko and Optitrack.

4. DISCUSSIONS

In this section we will summarize our experiences of working with the two systems in upper extremites of human body. The main assets of the Smart SuitPro is its portability and wireless capabilities. The total weight of the suit is approximately 19 cables and the whole system comes in a suitcase with the power battery. Comparably, one could argue that a 8-camera OPTITRACK setup could be portable, but this system requires tripods, which makes it more troublesome to transport and set up. OPTITRACK is also wireless, in the sense that the user only wears reflective markers with no cables, but the capture area is restricted to the volume that is covered by the cameras, whereas SmartSuitPro can easily, cover an area with a radius of more than 100 meters. When designing a system for real-time interaction based on OPTITRACK, possible marker dropouts due to optical occlusion or a marker being moved out of the capture area must be taken into account. For ROKOKO, we have not experienced complete dropouts like this, but the Bluetooth link is vulnerable in areas with heavy wireless radio traffic, which may lead to data loss. Nevertheless, we consider ROKOKO to be the more robust system for on-stage performances.

In the in vitro part of this study SmartSuitPro and OPTITRACK were calculated to RMSE values calculated as 0.95 degree and the results of the two systems were shown to be within a similar range in the Bland-Altman Figure 3.2. Although the RMSE was calculated as 8.25 degree in vivo experiments, it was observed that there were maximum of 4 data outside the upper and lower limits of the Bland-Altman Figure 3.13. The reason why more than 5% data in toothbrush movement is that this motion has combined degree of freedom in more than one plane In other in vivo experiments, 1 or 2 data is out of limit which less than the acceptable value of 5% due to reasons such as SmartSuitPro and OPTITRACK moving out of the working area during the experiment or being affected by noise in the environment are shown as in Figure 3.6. Also Table 3.3 shows the results of shoulder flexion also indicating that there is no problem in the analysis of the data.

Rokoko has the benefit of costing less than most other motion capture technologies with equivalent resolution in time and space. The full Rokoko suit is not comfortable to wear for a longer time period, whereas OptiTrack markers impose no or little discomfort. On the other hand, Opti-Track markers can fall off when tape is used to attach them. Rokoko has a similar problem with the foot attachments of its sensors, which seems to cause positional artifacts.

This project utilized a subject design in single plane. The goal was to propose a methodology that enables assessment of the degree of applicability of markerless technique in the clinical field with respect to joint motion estimation. In order to compare the performance of markerless and optical systems in terms of clinically relevant joint angles estimation, the same anatomical frames of reference must be defined for both systems. This is a crucial aspect when considering that optical system joint angles estimation strictly depends on joint embedded frame of references definition, while markerless ones are only related to technical frames that are far from been easily interpreted in a clinical context or from enabling comparison with state of art ROM analysis. The procedure that has been followed exploits the anatomical calibration performed in the optical protocol in order to substitute the technical frame of markerless technique with anatomical one. Joint angles calculated with optical and markerless technique were compared, and the difference was evaluated in terms of RMSE. RMSE was evaluated for each time point of each movements (flexion / extension, abduction / adduction, internal / external rotation) and then the mean RMSE over the shoulder and elbow was estimated. For the elbow joint, only flexion extension angle was determined as it was proven to be the only one reliable when reconstructed by means of optical technology.

In summary, since the in vitro experiment demonstrates that the Smart SuitPro system may be equivalent to the OptiTrack system, in vivo experiments are due to the lack of experience by volunteers to make the movements more accurate and smooth prior to the presence of out-of-limit data on the Bland-Altman graphs and RMSE high.

In further studies, it can be seen that if the volunteers do more practical experiments, the results of the Optitrack with SmartsuitPro will be less RMSE and the results will be more meaningful in the Bland-Altman graphs.

5. CONCLUSIONS

Both OptiTrack and Rokoko offer useful MOCAP data for biomechanical applications. They have some shared and some individual weaknesses, and in the end it is not the clinical data that matters, but the intended usage. If high positional precision is required, OptiTrack is preferable over Rokoko, but if acceleration values are more important, Rokoko provide less noisy data without occlusion problems. Overall, we find Rokoko to be the most robust and stage-friendly MOCAP system for real-time synthesis control.

In this thesis, only the upper extremity is studied in one plane and you are talking about the upper extremity human body, but you are not talking about the full body. In vitro and in vivo results yielded RMSE at 0.95° and 8.25° and high correlations according to Blad-Altman result. Although the RMSE values in the in vivo test results were high in some movements due to the inability of the volunteers not to perform the movements completely, the low RMSE and Bland-Altman results were significant and as mentioned about the RMSE and Bland-Altman results averagely high correlation in upper extremity of human body for this reason thesis study were equivalent to each other in upper extremity movements.

The overarching aim of this study is to provide evidence for the suitability of SmartSuitPro to be compatible with the biomechanical simulation tools. One of this simulation tools is Biomechanics of Bodies (BoB) software. In this software, input data is provided from the sensors of the SmarSuitPro and feed into the BoB software to calculate the ROM values.

Below a supplemantary work is provided to feed into BoB in an in vitro experiment to obtain data from SmartSuitPro as shown in Figure 5.1.

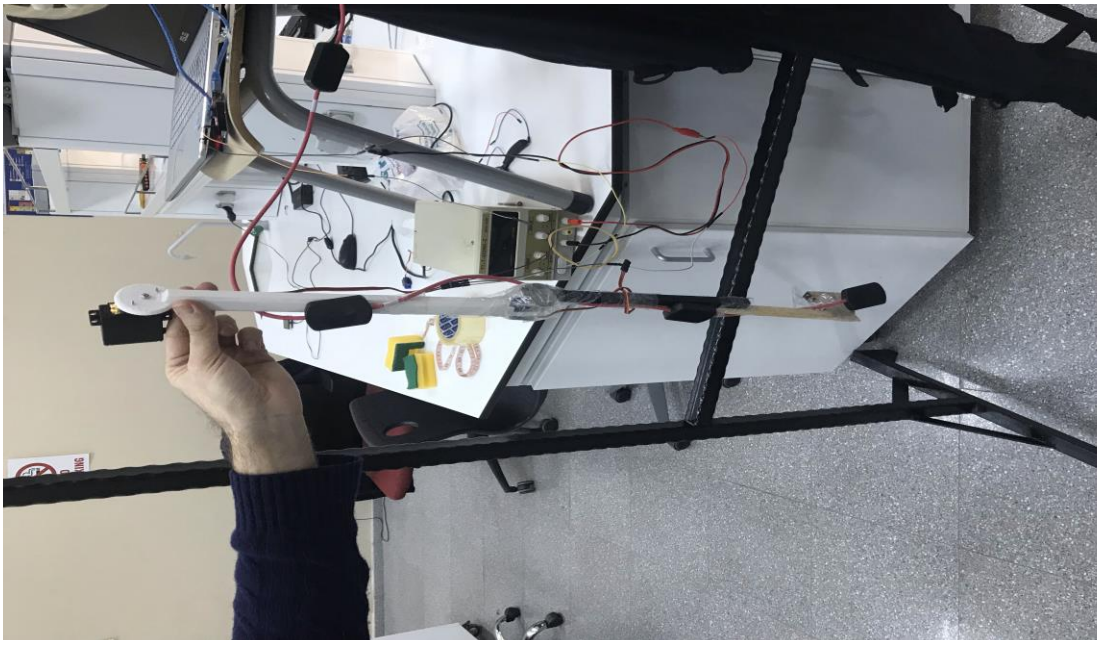
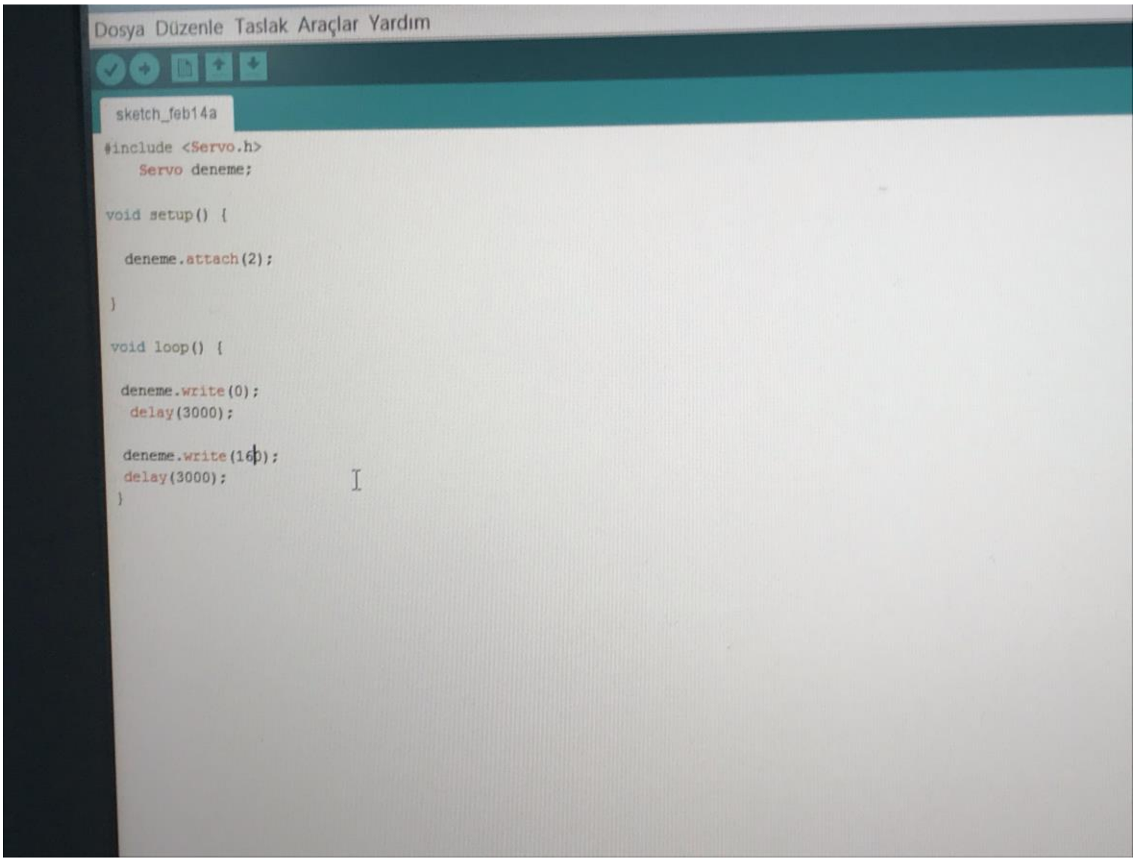


Figure 5.1 : In vitro experiment protocols for importing ROKOKO datas to BOB.

Experiment protocols were given 45 degrees signals with help of Ardunio in Figure 5.2 and how many degrees of ROM were calculated by creating two vectors from the data of the sensors placed on the shoulder, arm, forearm and hand.



```
#include <Servo.h>
   Servo deneme;

void setup() {

 deneme.attach(2);

}

void loop() {

 deneme.write(0);
  delay(3000);

 deneme.write(160);
 delay(3000);
 }
```

Figure 5.2 : The Ardunio code which give 45 degrees signals to in vitro experiment protocol.

Additionaly, ROKOKO data were transferred to BOB in bvh format and the 45 degrees ROM results from BOB. One sample of BOB result is shown below in Figure 5.3.

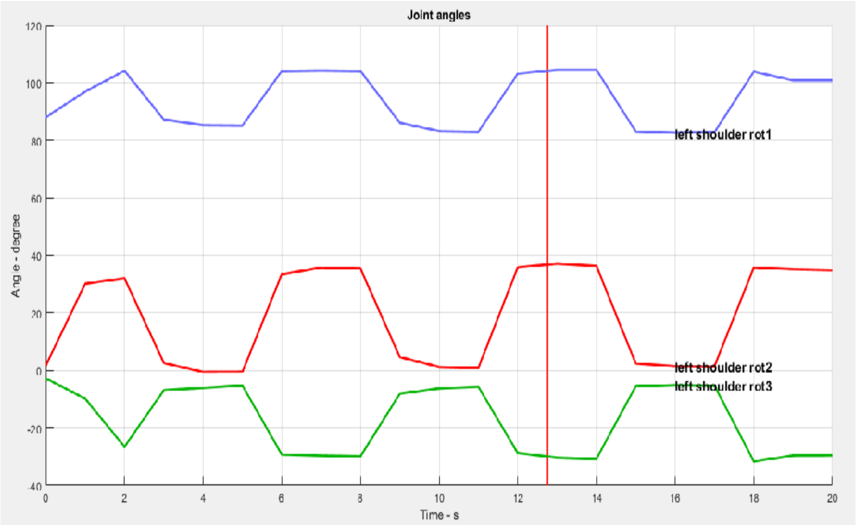


Figure 5.3 : BOB results of 45 degrees of ROM in vitro experiment.

45 degree of ROM was performed 3 times in each sample. In this study each sample have 5 ROM and a total of 15 ROM were obtained. The results of ROM are shown below in Table 5.1.

Tablo 5.1 : All samples of BOB results of ROM in vitro experiment.

EXPERIMENT	ROKOKO RESULTS	EXPERIMENTAL RESULTS
SAMPLE 1-1	38,7	45
SAMPLE 1-2	42,4	45
SAMPLE 1-3	41,3	45
SAMPLE 2-1	48,2	45
SAMPLE 2-2	46,9	45
SAMPLE 2-3	48,1	45
SAMPLE 3-1	42,5	45
SAMPLE 3-2	44,3	45
SAMPLE 3-3	45,6	45
SAMPLE 4-1	47,2	45
SAMPLE 4-2	48,3	45
SAMPLE 4-3	47,6	45
SAMPLE 5-1	44,1	45
SAMPLE 5-2	43,6	45
SAMPLE 5-3	45,3	45

In vitro experiment showed that we were able to transfer SmartSuit Pro data to BOB and the result of ROM in vitro RMSE were 2.78 degrees respectively for BOB and experimental results. Lower values of RMSE indicate better fit. According to BOB results of ROM and accuracy can be shown in the Bland-Altman Figure 5.4.

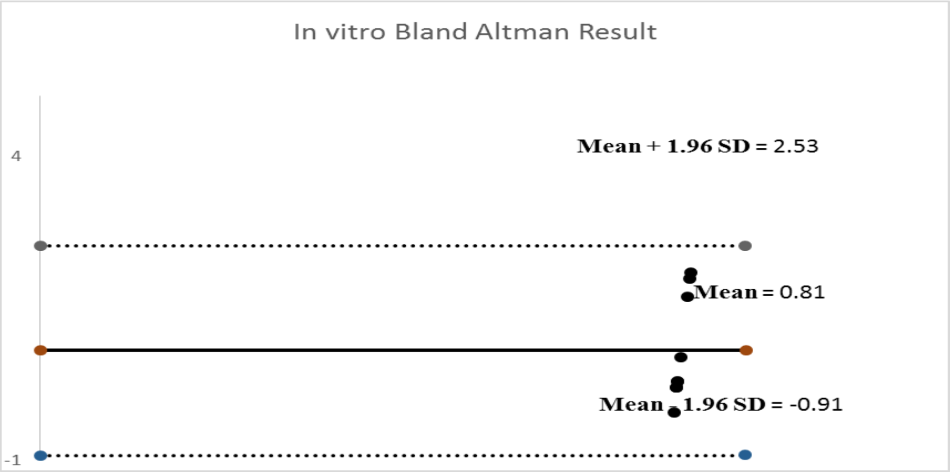


Figure 5.4 : In vitro Bland-Altman result of BOB 45 degrees ROM.

Since this thesis focused only on the upper body kinematics the next task in further studies is to conduct an experimental setup for gait analysis and qualify the Smart SuitPro pro data by feeding them into to BoB. The data can be used also to extract kinetic data using BoB.

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7. APPENDIX

7.1 Appendix 1

VOLUNTARY BRIEFING and APPROVAL FORM

This is your experiment, scientific study name is ‘ The Measurement of Range of Motion with Rokoko and Optitrack on Physiotherapy Exercies and Daily Routine'. The Rokoko Smartsuit and Optitrack sensors to be used in this study will be placed and calibrated. Before starting the experiment, the movements of abduction, flexion and daily routine movements such as tooth brushing and hair combing are shown then the movements are repeated 10 minutes for warm up. Once the experiment has begun, it will be said to repeat the movements 3 times. The volunteers will be rested by taking breaks between the movements. It will take about 45 minutes to get data from brushing teeth and hair combing movements. This research does not carry any unwanted effects or risks for you. This study will be conducted between January - April 2019. This research will be conducted with approximately 3 male and 3 female participants. As part of this research, no fees will be charged from you, no fees will be charged from the Social Security Institution to which you are affiliated and no fees will be paid to you. Taking part in this research is entirely up to your will. You can refuse to participate in the research or leave the research at any stage; this will not interfere with any criminal or other benefits. If you do not fulfill the requirements of the work schedule applied within or outside your investigator's knowledge, disrupt the work schedule, and so on. for reasons, he can remove you from the investigation. The results of the study will be used for scientific purposes; if you withdraw from the study or are removed by the investigator, medical data relating to you may be used for scientific purposes if necessary. All of your medical and identity information will be kept confidential and even if the research is published, you will not be given your identity information, but you will have access to your medical information when necessary. You can access your own medical information at any time. I read the text above that shows the information that should be given to the volunteer before the investigation. I have been given written and oral explanations about these. I agree to participate in this clinical trial without any repression or coercion.

Name Surname : **Signature** :

Telephone Number : **Address** :

7.2 Appendix 2

EXPERIMENT EVALUATION FORM

DATE:_____________

NAME:

SURNAME:

HEIGHT:

WEIGHT:

JOB:

AGE:

GENDER: **FEMALE / MALE**

ROKOKO DATA RESULTS

		Physiotherapy Exercies			Daily Routine		
		1.Test	2.Test	3.Test	1.Test	2.Test	3.Test
Range of Motion	Typical						
FLEXION	0º -180º						
ABDUCTION	0º -180º						
INTERNAL ROTATION	0º - 90º						
EXTERNAL ROTATION	0º - 90º						
EXTENSION	0º - 45º						

OPTITRACK DATA RESULTS

		Physiotherapy Exercies			Daily Routine		
		1.Test	2.Test	3.Test	1.Test	2.Test	3.Test
Range of Motion	Typical						
FLEXION	0º -180º						
ABDUCTION	0º -180º						
INTERNAL ROTATION	0º - 90º						
EXTERNAL ROTATION	0º - 90º						
EXTENSION	0º - 45º						

7.3 Appendix 3

Ethics Committee Approval

0722

T.C.
İZMİR KÂTİP ÇELEBİ ÜNİVERSİTESİ
Girişimsel Olmayan Klinik Araştırmalar Etik Kurulu Karar Formu

Sayın Prof. Dr. Aliye TOSUN

Karar No: **432**
Tarih : **19.12.2018**

KARAR

Yenilikçi bir hareket takip ve değerlendirme sistemi araştırma başvuru dosyanız kurulumuzda gerekçe, amaç, yaklaşım ve yöntemleri dikkate alınarak incelenmiştir. İnceleme sonucunda çalışmanın başvuru dosyasında belirtilen merkezlerde gerçekleştirilmesinde **etik ve bilimsel açıdan sakınca bulunmadığına** toplantıya katılan etik kurul üyelerinin **OYÇOKLUĞU** ile karar verilmiştir.

Doç. Dr. Orhan GÖKALP
Başkan

Doç. Dr. Serdar BAYATA
Başkan Yardımcısı

Prof. Dr. Yasemin TOKEM
Üye

T.KATILMADI
Prof. Dr. Belde Kasap DEMİR
Üye

Doç. Dr. Özgür TOSUN
Üye

Doç. Dr. Aslı BAYSAL
Üye

T.KATILMADI
Uzm. Dr. Ayşenur ATAY
Üye

T. KATILMADI
Dr. Mehmet ERTAN
Üye

Uzm. Dr. Doğu Barış KILIÇÇIOĞLU
Raportör Üye

Dr. Öğr. Üyesi Gülay OYUR ÇELİK
ÜYE

KARŞI OY :

*Çalışmanın İlaç ve Tıbbi Cihaz Kurumundan izin alınması koşulu ile onaylanmasının uygun olacağı,
*Çalışmanın İlaç ve Tıbbi Cihaz Kurumundan izin alınması koşulu ile onaylanmasının uygun olacağı

0722

T.C.
İZMİR KÂTİP ÇELEBİ UNIVERSITY
Non-Interventional Clinical Studies
Institutionel Review Board

To : **Aliye TOSUN, MD**
From : Assoc. Prof. Orhan GÖKALP, MD, Chair
Date : **19.12.2018**
IRB # : **432**
Study Title : A novel motion capture and assessment system.

At its board meeting **19.12.2018** your submission for the above referenced research study has received review and approval from İzmir Kâtip Celebi Non-Interventional Clinical Studies Institutional Review Board.

Assoc. Prof. Orhan GÖKALP

CURRICULUM VITAE

PERSONAL INFORMATION		
NAME,SURNAME	:	**HAKKI KOSE**
T.C. NUMBER		**34525894370**
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PHONE NUMBER	:	0553 187 87 20
E-MAIL ADDRESS	:	hkose3434@gmail.com
BORN DATE	:	10/10/1990
MARITAL STATUS	:	Married
EDUCATIONAL BACKGROUND		
2015-		• **IZMIR KATIP CELEBI UNIVERSITY,IZMIR** Master, Biomedical Technologies
2009 – 2014		• **YEDITEPE UNIVERSITY, ISTANBUL** Undergraduate Education, Biomedical Engineering
2005 – 2009		• **Kırımlı Fazilet Olcay Anadolu Lisesi, ISTANBUL** High School
BUSINESS EXPERIENCE		
	20/03/2016 – 12/01/2017	• Platinum Tıbbi Aletler – Production Enginnering and Sales and marketing manager
	08/08/2014 – 17/08/2014	• ANADOLU SAĞLIK MERKEZI JOHN HOPKİNS HOSPITAL, Zorunlu Staj Maintenance, repair and calibration of medical devices.

	04/06/2013 – 09/07/2013	• ANADOLU SAĞLIK MERKEZI JOHN HOPKİNS HOSPITAL, Zorunlu Staj • Maintenance, repair and calibration of medical devices.

COMPUTER KNOWLEDGE

- Auto INVERTER I received training in Izmir Katip Celebi University.
- SolidWORKS I received training in Izmir Katip Celebi University.
- Matlab , I received training in Yeditepe University.
- C++ , I received training in Yeditepe University.
- Microsoft Office I received training in Yeditepe University.
- Autocad , I received training in Yeditepe University.

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PROJE

- MANUAL DETERMINATION OF THE REGION RELATED TO BREAST MR IMAGES (Undergraduate graduation project)

CERTIFICATES

- General Patent Training Certificate
- Medical Calibration Education Certificate