FINAL DEGREE PROJECT

Bachelor's Degree in Biomedical Engineering

COMPARISON OF JOINT KINEMATICS OBTAINED WITH AN OPTICAL CAMERA SYSTEM AND A DEPTH CAMERA

Report

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Resum

La societat actual ja fa anys que mostra una tendència cap a la digitalització i la semipresencialitat en tots els àmbits, però han sigut els darrers dos anys els que ens han mostrat la necessitat de portar aquesta digitalització a la medicina. És evident que cada vegada hi ha més recursos que permeten fer visites mèdiques o tractaments a distància, per tal que ni els pacients ni els professionals sanitaris hagin de desplaçar-se. La telemedicina proporciona les eines que fan possible la medicina a distància. El fet de poder realitzar determinats tractaments a distància permet ajudar a molts pacients a accedir als tractaments sense haver de desplaçar-se.

Aquest projecte està enfocat a l'anàlisi de la precisió a nivell cinemàtic de les dades que s'obtenen amb un sistema de captura del moviment de baix cost, com és una càmera de profunditat. Aquesta càmera s'està utilitzant per desenvolupar un sistema de telerehabilitació de pacients que han patit un ictus i que, a causa d'aquest, han perdut mobilitat física. El sistema de telerehabilitació consisteix en una aplicació computacional que conté exercicis i jocs que l'usuari ha de seguir, i la càmera de profunditat, utilitzada en aquest treball, que permet registrar els moviments del pacient i calcular-ne els paràmetres necessaris.

Per a realitzar aquesta demostració s'ha fet una comparació de les mesures cinemàtiques i de diversos subjectes enregistrades amb una càmera de profunditat (de baix cost) i amb un sistema de càmeres òptiques (que tenen un cost alt i requereixen una infraestructura molt més complexa).

Resumen

La sociedad actual ya hace años que muestra una tendencia hacia la digitalización y la semipresencialidad en todos los ámbitos, pero han sido los últimos dos años los que nos han mostrado la necesidad de llevar esta digitalización a la medicina. Es evidente que cada vez hay más recursos que permiten hacer visitas médicas o tratamientos a distancia, para que ni los pacientes ni los profesionales sanitarios tengan que desplazarse. La telemedicina proporciona las herramientas que hacen posible la medicina a distancia. El hecho de poder realizar determinados tratamientos a distancia permite ayudar a muchos pacientes a acceder a los tratamientos sin tener que desplazarse.

Este proyecto está enfocado al análisis de la precisión a nivel cinemático de los datos que se obtienen con un sistema de captura del movimiento de bajo coste, como es una cámara de profundidad. Esta cámara se está utilizando para desarrollar un sistema de telerehabilitación de pacientes que han sufrido un ictus y que, a causa de este, han perdido movilidad física. El sistema de telerehabilitación consiste en una aplicación computacional que contiene ejercicios y juegos que el usuario tiene que seguir, y la cámara de profundidad, utilizada en este trabajo, que permite registrar los movimientos del paciente y calcular los parámetros necesarios.

Para esta demostración se ha realizado una comparación de las medidas cinemáticas de varios sujetos grabadas con una cámara de profundidad (de bajo coste) y con un sistema de cámaras ópticas (que tienen un coste alto y requieren una infraestructura mucho más compleja).

Abstract

Today's society has for years shown a trend towards digitalization and half on-site treatment in all areas, but it is the last two years that it has shown us the need to bring this digitization to medicine. More and more resources allow for remote medical visits or treatments, so neither patients nor health professionals have to travel. Telemedicine provides the tools that make medicine possible at a distance. The fact that certain treatments can be performed at a distance allows many patients to access treatment without having to move around.

This project focuses on the analysis of the kinematics accurate data obtained with a low-cost motion capture system, such as a depth camera. This camera is being used to develop a tele-rehabilitation system for patients who have suffered a stroke and who, as a result, have lost physical mobility. The telerehabilitation system consists of a computer application that contains exercises and games that the user must follow, and the depth camera, used in this work, allows the patient to register the movements and calculate the parameters necessary.

To perform this demonstration, a comparison of the kinematic measurements of various subjects recorded with a low-cost camera (depth camera) and an optical camera system (which has a high cost and requires much more complex infrastructure) was performed.

Acknowledgements

First, I would like to express my gratitude to Gil Serrancolí Masferrer, my tutor, who without his help this project would not have been possible, he provided feedback on all the programs to be used, the performance of both optical cameras and depth cameras and the codes to be used.

I would also like to thank Andrés García Orozco, Andrea Iriarte Gea, and Carles Margelí who created the application Nuitrack, used in this project to record the data from the depth camera.. I would like to thank Francesc Serrate, who printed in 3D the calibration square needed.

Finally, I would like to thank all the volunteers who offered to be recorded performing the exercises and the SIMMA lab of the EEBE for letting me use their facilities.

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1. Preface

Origin of the project

This project has been developed at the SIMMA Lab (Simulation and Movement Analysis Lab) of the EEBE (Escola d'Enginyeria de Barcelona Est). It is a contribution to a previous study started by Jordi Torner, Gil Serrancolí and Francesc Alpiste, and a further final degree project done by Andrés García Orozco, Andrea Iriarte Gea [1]. Both pieces of research are studies that are aimed to improve the rehabilitation therapy of patients who have suffered from strokes and who have lost cognitive and motor skills.

Carles Margelí, Andrés Garcia and other students of EEBE, created a VR application that allows patients to work on their rehabilitation exercises following games. The patient is recorded by a depth camera, then the application displays a character that represents the moves made by the person. Carles Margelí adapted the application for this project, where it exports the trajectory of the skeleton's points. Afterward, the data file can be processed by a Matlab code [2] which calculates the joint angles.

Motivation

There are several reasons why this thesis was chosen. First of all, as a Biomedical Engineering student, I have been able to observe the great need to bring technology to the field of medicine. Technology can improve many areas of the health system, making it more efficient, cheaper, and more reachable to more people.

One of the applications of technology in medicine is telemedicine. Telemedicine eases access to medical treatments for patients that have difficulties going to the medical facilities. Patients who do not live in a big city and do not have big hospitals nearby can benefit from telemedicine, which saves them unnecessary on-site health visits. It is also very complicated for people that have suffered an accident, disease, or condition and have low mobility capacities.

Technology is not always cheap and easy to use, that is why this project is focused on demonstrating that low-cost tools can be perfectly used in telemedicine and by any person with basic computer skills.

Previous requirements

To be able to work on this project and get results previous acknowledgment was required. First, it is needed to have a previous insight into some computer programs, like OpenSim or Matlab. Then, the subject pursued in Movement Simulation has been very useful to understand easily the concepts of angle calculations and the kinematic studies with OpenSim.

2. Introduction

This project aims to demonstrate that it is possible to perform rehabilitation therapies from home with an adjusted budget. To do telerehabilitation it is necessary to ensure that there is an infrastructure that allows the doctor to check if the patient is doing correctly the exercises and if the patient is improving their physical “abilities”.

For this reason, the first tool that is needed to perform telerehabilitation is a camera that records the patient's exercises. But if the camera only records the exercises there is no way to know if the patient is showing any improvements. That is why the camera that is going to be used has to be able to give information. Several systems give information and record the patient. The two options that this project is comparing are an optical camera system and a depth Camera. These two systems have many differences.

First of all, the optical camera systems are a way more expensive system, since just the cameras suppose approximately 600€ each, plus the hubs that are 300€ each. On the contrary, depth cameras have a price of less than 300€, with no need for any hub.

Another advantage of the depth camera is that it is simpler and needs fewer accessories; it is only a small camera connected by a USB cable to the computer. The camera can be positioned on the table on a small tripod. The optical camera system is a whole infrastructure, it needs at least six cameras, one or two hubs, and all the cables to connect the cameras to the hubs and the hubs to each other and the computer. The cameras have to be at a considerable high (at least 2m from the floor), so they need to be on high tripods or support from the ceiling.

This project compares the results of the measurements obtained with these two systems to prove that the depth camera, which has already been used in research projects, can be used for telerehabilitation providing good results.

Objectives

The main goal is to proof that the precision of the results obtained with a low-cost telerehabilitation system are acceptable. But to demonstrate it, more specific goals have been established:

- To understand how the Optical Camera System and the Depth Camera work.
- To install the Optical Camera System and solve any problem that might come with it.
- To learn all the needed tools from Motive and Nuitrack.

- To get as many volunteers as possible to record their exercises.
- To be able to record at the same time with the Optical Camera System and the Depth Camera.
- To process all the data from both systems.
- To compare the measurements obtained by both systems.
- To get a reasonable conclusion based on the results of the comparison.

Scope

The scope of this project is to calculate by different methods the joint angles of different subjects. The number of subjects is 5. The optical camera system should be hanging from the ceiling to ensure better recording quality, and the windows should be completely covered. As the resources and time are limited, this project has some limitations and this has affected the obtained results.

This project is an introduction to what could be a scientific paper with more reliable data results. It should count with more subjects and exercises, and to have the cameras fixed at support from the ceiling, ensuring that they do not move during the experiment. Also the windows should be completely covered, ensuring there are no reflections during the recording sessions.

3. Telerehabilitation

State of the art

The use of telemedicine has shown a growing trend for many years with the improvement of technologies. But in the last 3 years, due to the Covid19 pandemia [3], it has been introduced to several areas of medicine. One of the areas where telemedicine has been introduced is telerehabilitation. It can be considered an area of telemedicine [4].

Rehabilitation can be performed remotely thanks to the advances in communication devices. Patients can keep in touch with the medical staff without having to travel to the medical facilities. The fact that rehabilitation can be followed from home helps different sectors of the population. First, it helps people who live far from medical centers and before these treatments they had to do long-distance journeys to get to the hospital, also not all people have their means of transport and had to take a taxi or ask their relatives and friends. Another sector of the population for whom telerehabilitation can be very helpful are the patients who suffered diseases or accidents that have caused them serious mobility problems. For them, having to travel to the hospital can be very complicated.

When performing telerehabilitation it is very important to have good communication between the medical response and the patient or the person who is taking care of the patient at home. It is very important to transmit correctly all the information about the exercises and anything that has to do with the therapy. Although communication is very important it is not the only thing to consider, there must exist some kind of video recording from the patient to the doctor. Videos can show if the person is doing the exercises correctly. But, even with excellent communication and high-quality videos of the exercises, the physical therapist or the doctor has to visit the patient to check the improvements. To do this at home, some sort of technology is needed to allow the tracking of some clinical parameters. There are studies [5] [6] that use sensors to give the needed parameters. There has also been some research [7] about using Kinect technology to give information about the improvements of the patients.

Applied to stroke rehabilitation

Stroke causes in many cases disability for life or long-lasting [6]. Patients who have suffered a stroke experiences a reduction in their motor skills. This makes it very difficult for them to be able to get to the hospital for themselves. For this reason, telerehabilitation can be very useful for them.

Although nothing has gone further than research, there are experimental therapies [5] that use wearable sensors to get the parameters that show the improvement of the patient. Others use infrared light technology, like depth cameras, to avoid having to use any sensor. The studies [7] that use depth cameras result simpler and easier to use for patients because they almost do not need any installation, and it only needs to be put in a place that can catch the subject correctly, like a table.

Software techniques to evaluate improvements in telerehabilitation

In addition to the camera system that is going to be used to control the rehabilitation therapy, it is needed to have software tools that process the obtained data. Clinical variables that allow the clinicians to know if the patient is improving their mobility skills are the joint angles. The joint angles can be calculated by de data recorded by depth camera or an optical camera system.

Two techniques to obtain the joint angles has been used (inverse kinematics analyses). Optical camera systems use the OpenSim Inverse kinematics tools, and we used a custom MATLAB code to obtain joint angles using the depth camera.

4. Optical camera system

Optical camera systems are groups of cameras that detect markers from an object. The cameras are spread around a room focusing on the object that has the reflective markers. Each reflective marker corresponds to a joint, muscle, or bone from a model. Then, by using the software Motive, the markers are labeled and saved in a data file with the position of each marker at every time frame.

4.1. Optitrack Flex 3 optical camera system

The optical camera system that has been used is an Optitrack Flex 3 system from NauturalPoint (Naturalpoint, Corvallis, OR, USA). The system consists of 6 cameras (Figure 4.1). The cameras are spread around the lab focusing on the subject to be recorded, who has to be placed in the middle of the cameras (Figure 4.2). Each camera stands on a tripod; 4 tripods are high enough to place the cameras to more than 2 m from the floor and 2 tripods to hold the other cameras at the high of a table. The cameras are connected to the computer by 2 hubs and the corresponding connections.

Figure 4.1. Optitrack Flex 3 camera [8]

Figure 4.2. Example of a distribution of the cameras in a room [8]

4.1.1. Device specifications

The Flex 3 cameras are a compact system that can be customized. The model offers fast, precise, and efficient tracking. This is very important for the project because the results will depend on the quality and the speed that the cameras can capture. They have a price of 659€ each. The detailed specifications of the cameras are the following [9]:

<u>Camera Body:</u>

- Width: 1.78 inches (45.2 mm)
- Height: 2.94 inches (74.7 mm)
- Depth: 1.44 inches (36.6 mm)
- Weight: 4.20 ounces (0.1 kg)
- Mounting: 1/4"-20 tripod thread
- Status Indicator: 2 digit numeric LEDs

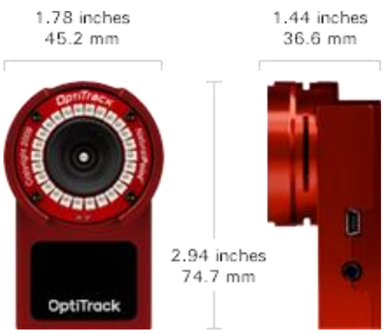

Figure 4.3. Camera dimensions [9]

LED Ring

- 26 LEDs
- 850 nm IR
- Adjustable brightness
- Strobe or Continuous Illumination
- Removable

Lens & Filter

- Stock Lens: 4.5 mm F#1.6
    - Horizontal FOV: 46°
    - Vertical FOV: 35°
- Optional Lenses:
    - 3.5 mm F#1.6
        - Horizontal FOV: 58°
        - Vertical FOV: 45°
- M12 Lens Mount
- Adjustable focus w/ spring assist
- 800 nm IR long pass filter
- Optional: 800 nm IR long pass filter w/ Filter Switcher

Image Sensor

- Imager Size: 4.5 mm × 2.88 mm
- Pixel Size: 6 µm × 6 µm
- Imager Resolution: 640 × 480 (VGA, windowed from 752 × 480)
- Frame Rate: 25, 50, 100 FPS
- Frame decimation (transmit every Nth frame)
- Spatial decimation: 320 × 240, 160 × 120
- Latency: 10 ms
- Shutter Type: Global
- Shutter Speed:
- Default: 1/1000th of a sec. (1 ms)
- Minimum: 1/50,000th of a sec. (20 µs)

Image Processing Types

- Object
- Segment
- Precision Grayscale
- MJPEG Grayscale
- Raw Grayscale

Input/output & Power

- Data: USB 2.0
- Camera Sync: USB 2.0 or Wired Sync
- Power: USB 2.0
    - Standard: 5V @ 490mA
    - High Power: 680mA

4.1.2. Wiring

The cameras must be correctly connected to a hub, which in turn is connected to a computer. There are certain limitations and requirements with the hubs and cables to do the connections. The cameras are connected by a USB cable to the hub and the hub is connected by a USB cable to the computer. To obtain an appropriate connection, two hubs (master and slave) have been used. Cameras 1, 2, and 3 are connected to the master hub, and cameras 4, 5, and 6 are connected to the slave hub. The slave hub is connected to the master hub, the master hub is connected to the computer, and both hubs are connected to the power by a power adaptor 230-12V. The following scheme [10] shows the connections (Figure 4.4).

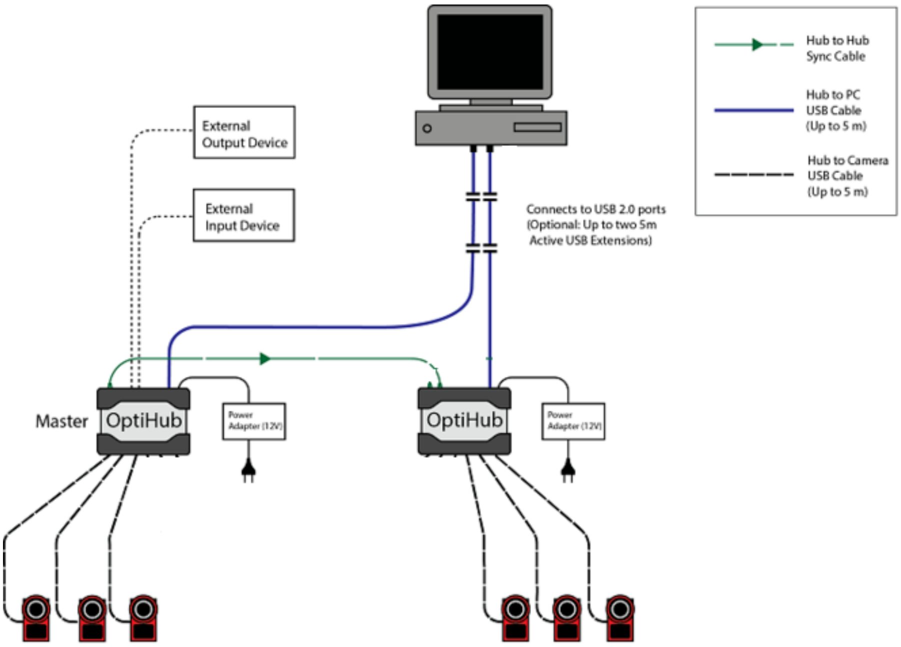

Figure 4.4. Wiring and cabling scheme of the optical camera system at the SIMMA lab [10]

There are some limitations with the cables used (Figure 4.4). The cable that connects the camera to the hub must not exceed 5m and has to be a single cable. The cable that links the master hub to the slave hub has to be a single cable and must not exceed 5 m. For the last cable, the one that links the master hub to the computer USB extensions can be used as long as the total length does not exceed 5m. The connection to the PC must be with USB 2.0 ports.

4.1.3. Collocation of the cameras

The cameras are placed around the SIMMA lab focusing on the position where all subjects will be sitting while performing the movements. To show the distribution of the cameras the following 3D simulation has been designed (Figure 4.5) [11]. A 2D plan has automatically created from the 3D model (Figure 4.6) [11].

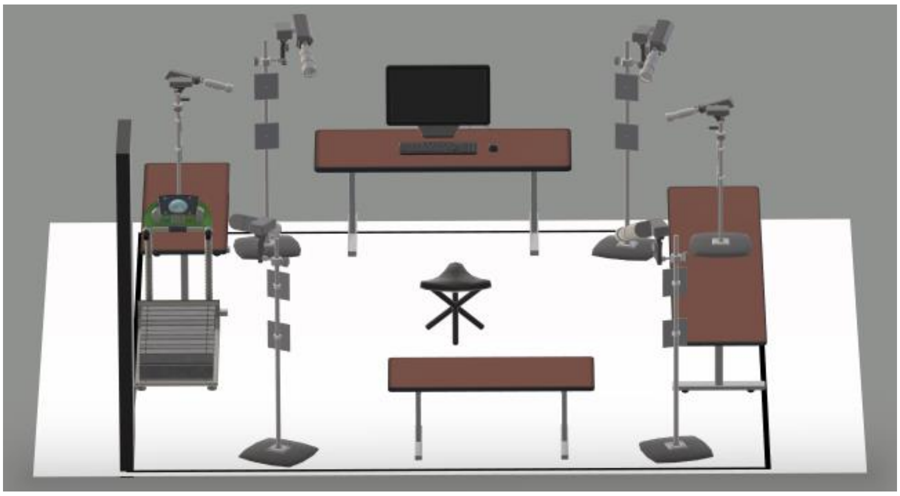

Figure 4.5. 3D SIMMA lab simulation [11]

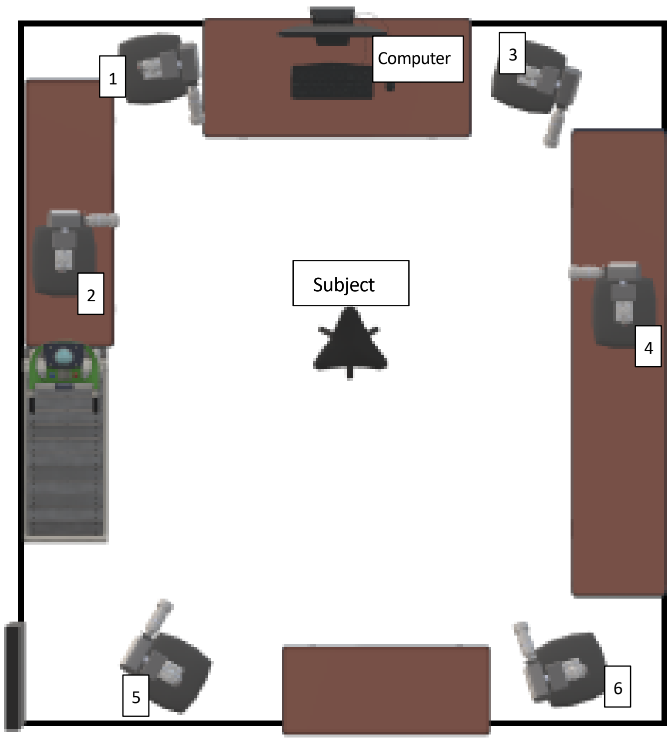

Figure 4.6. 2D plan of the SIMMA lab simulation [12]

4.1.4. Hubs

At the beginning, a regular hub from Amazon was used, but it brought connectivity problems with the cameras. Then, one "*Optihub 2"* from Optitrack (Figure 4.7) [13] was bought, but as the hub was located too far from some of the cameras and the cables were not long enough it was necessary to connect more than one cable from some of the cameras to the hub. This led to errors when trying to calibrate or record any take, and the solution was to acquire another *Optihub 2*.

Figure 4.7. Optihub 2 from Opittrack [13]

4.2. Motive

Motive is the computer program employed to record the movements with the Optical camera system (from NaturalPoint). It is a complex program with many tools, but it works in a very intuitive way. Also, the Optitrack webpage has a guide [14] with all that is necessary to know to work with the program.

It is necessary to follow four basic steps to obtain a good take. The calibration part is only needed at the beginning of each day to be recorded, regardless of the number of subjects registered. The labeling and data export parts are necessary for each take of each subject. The following subsections are written as a tutorial for future uses.

4.2.1. Reflections mask and calibration

Before recording any movement, it is necessary to mask any reflections that may appear. To do this it is necessary to open Motive in Live mode, then click "Perform Camera Calibration" (Figure 4.8) on the pop-up page that appears every time the program launches to open the Calibration Pane [15].

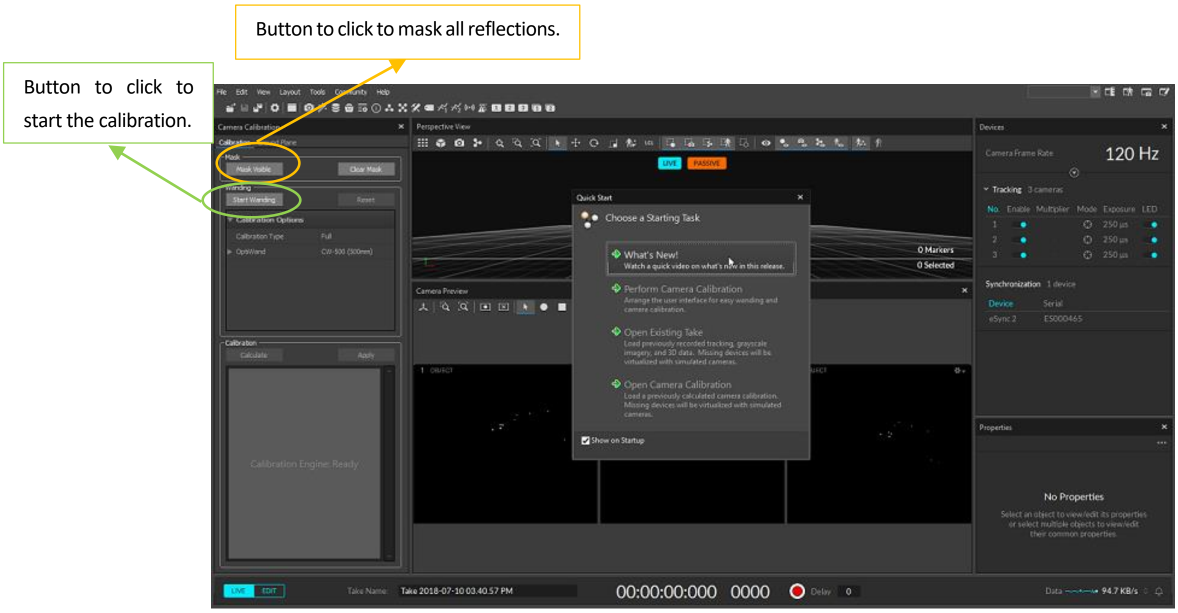

Figure 4.8. Calibration pane [15]

The next step is to calibrate the system by using the Calibration Wand CW-500 from Optitrack [16]. This tool (Figure 4.9) consists of an aluminum bar attached to another aluminum bar with three reflective markers. With the calibration pane opened, the "Start Wanding" button (Figure 4.10) is clicked and the calibration starts. The calibration has to be done to orientate and locate the cameras between them and to cover as many pixels as possible of the room where the captures will be recorded.

Figure 4.9. Calibration Wand [16]

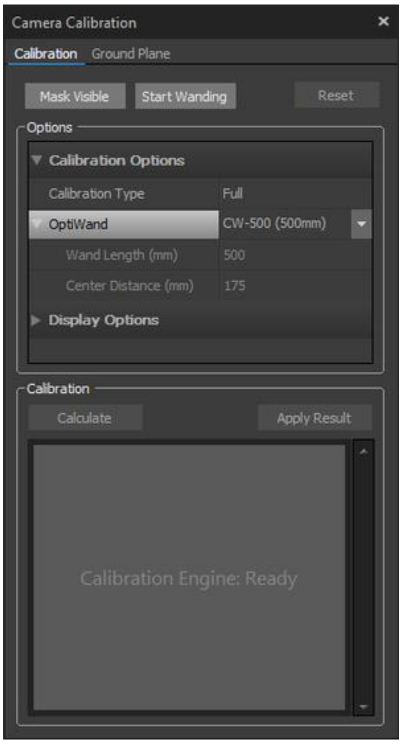

Figure 4.10. Calibration options [15]

To obtain a proper calibration, the calibration wand has to sweep the entire space where the movement will be captured, until the calibration summary table (Figure 4.11) turns green. Once the calibration is done, a message will appear with the calibration results (Figure 4.11). It is highly recommended to get "exceptional", or at least "excellent". Then, the "Apply" button is clicked and the wanding process is done.

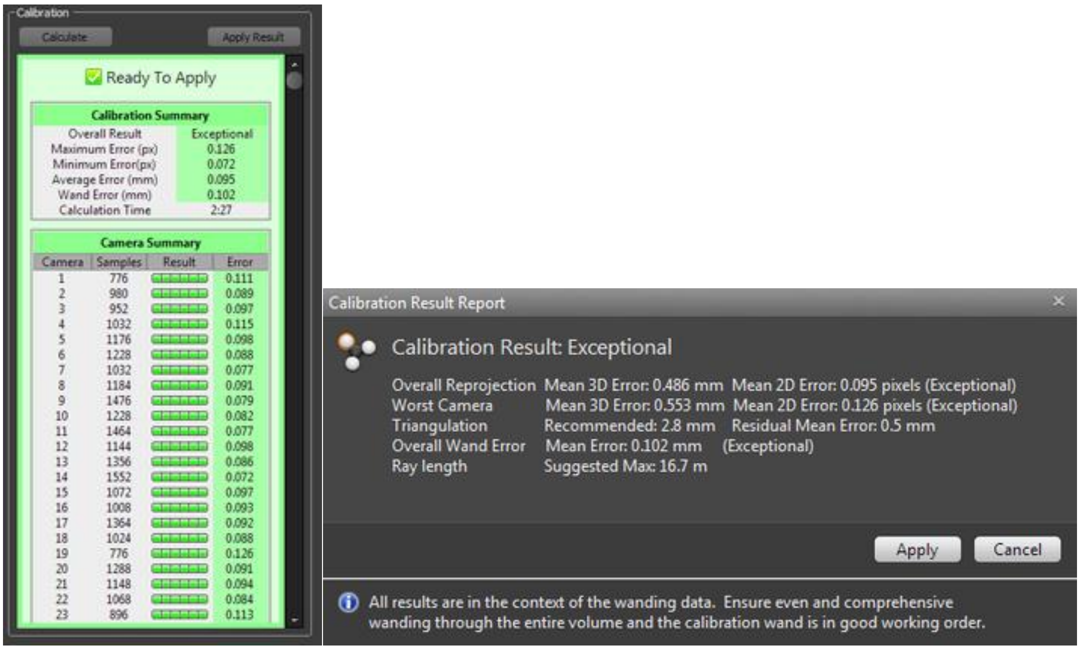

Figure 4.11. Calibration summary table and results message [15]

The final step before recording any data is to set the ground plane. For this, it is necessary to use the calibration square[17] (Figure 4.12). Instead of buying it, a 3D model was printed from the 2D plan [18] of the square, to reduce costs.

Figure 4.12. CS-200 Calibration Square [17]

To set the ground plane in Motive and to establish the origin of coordinates, the idea is to place the calibration square on the floor, in a place where it can be captured by all cameras [19]. Then, click the "Set Ground Plane" (Figure 4.13-left), and the 3 markers from the calibration square should be shown on the screen (Figure 4.13-right). The calibration data is automatically saved in the session folder.

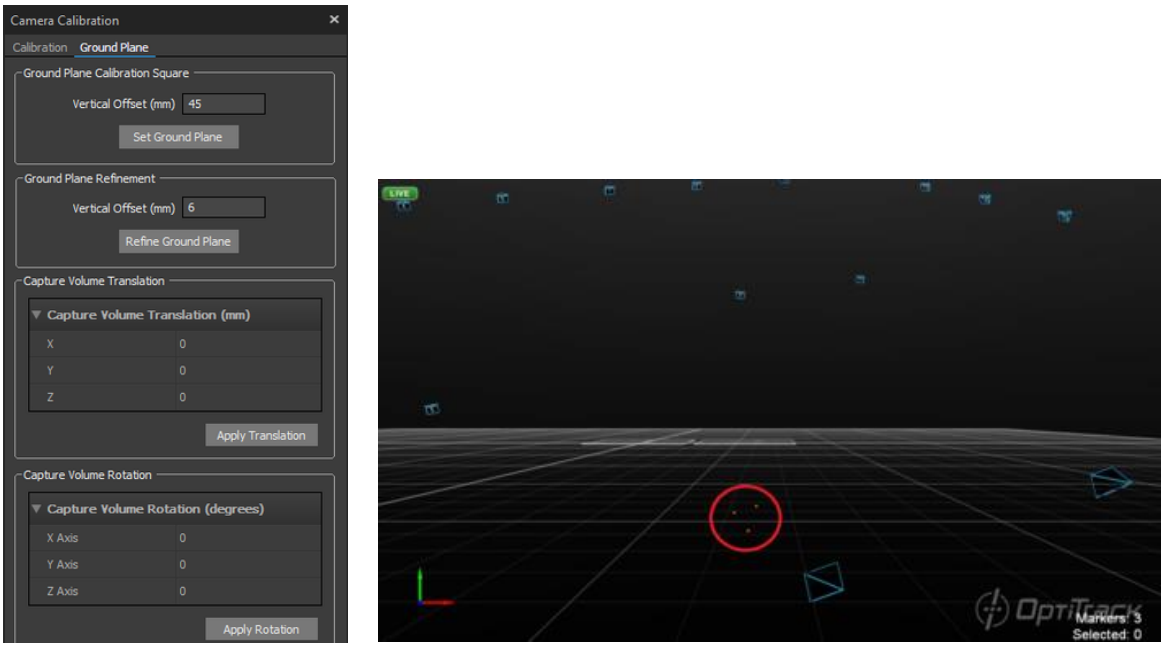

Figure 4.13. Ground Plane Options // Ground set that shows the markers on the floor [19]

4.2.2. Recording of movements

After the calibration and setting the ground plane, the system is prepared to record the subjects. To do it, it is necessary to open the "Live Mode" page (Figure 4.14) [20]. To start recording, the "recording button" (Figure 4.14) must be clicked. The time delay to start the capture can be set within the time delay button (Figure 4.14). In particular, for this project, as the captures from the optical camera system were recorded at the same time as the ones from the depth camera, a delay of 5 seconds was set. All takes are saved automatically in the session folder, the same folder where the calibration data has been saved.

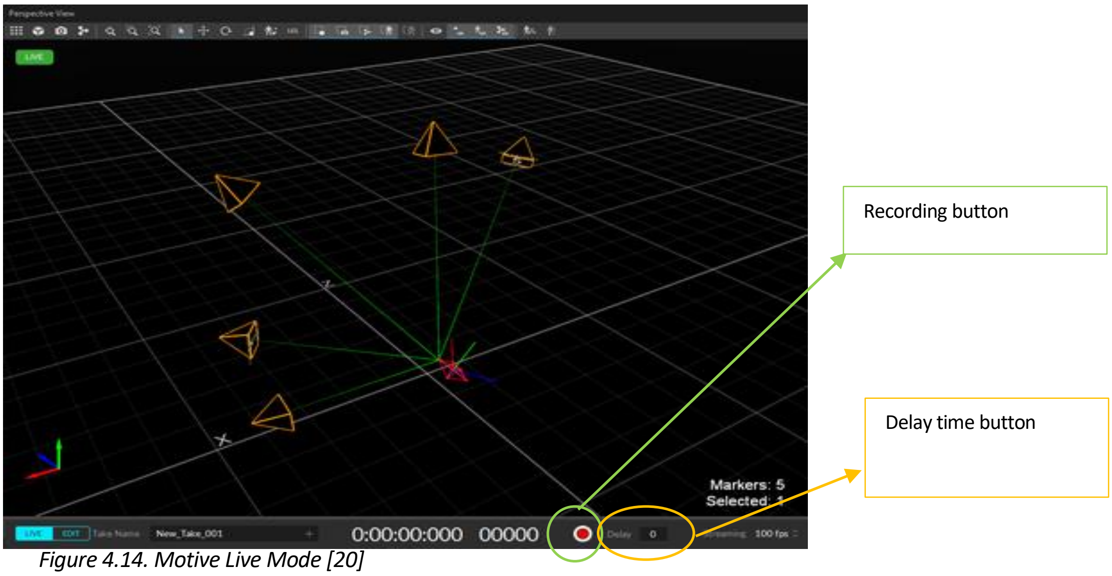

Figure 4.14. Motive Live Mode [20]

4.2.3. Labeling

The labeling process is the step that takes more time, as it is a very manual procedure. It works in the "Edit Mode". First, with a recorded take file opened, a marker set must be created containing all markers from the chosen model. The marker set created can be saved and be used for all takes.

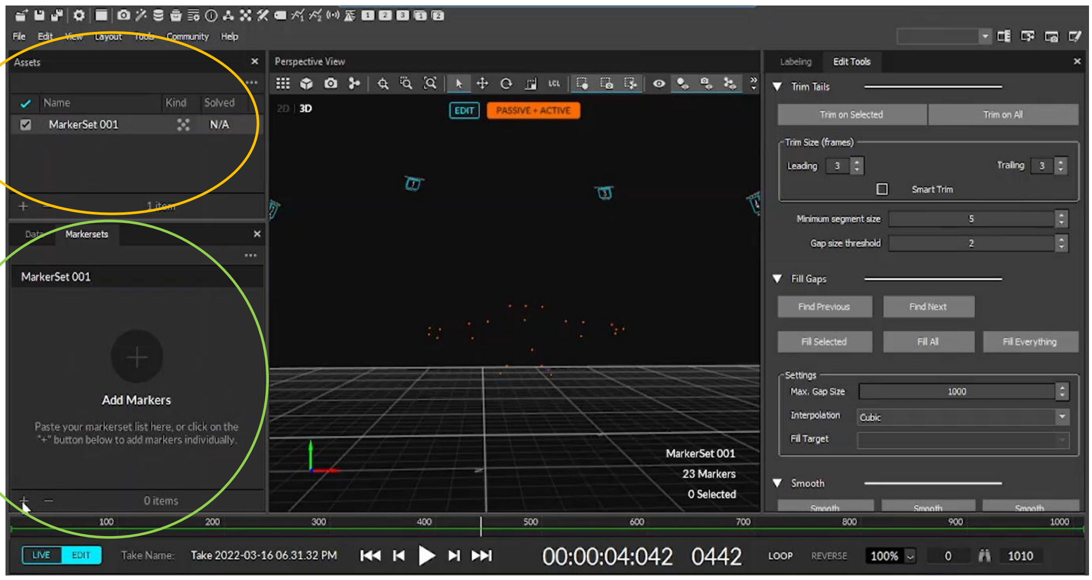

Figure 4.15. Markersets and Assets pane [21]

Second, it is necessary to "Reconstruct and Auto-label" (Figure 4.16) to obtain larger % for all "Unlabeled" markers. This step can be done several times in different time frames to obtain better results.

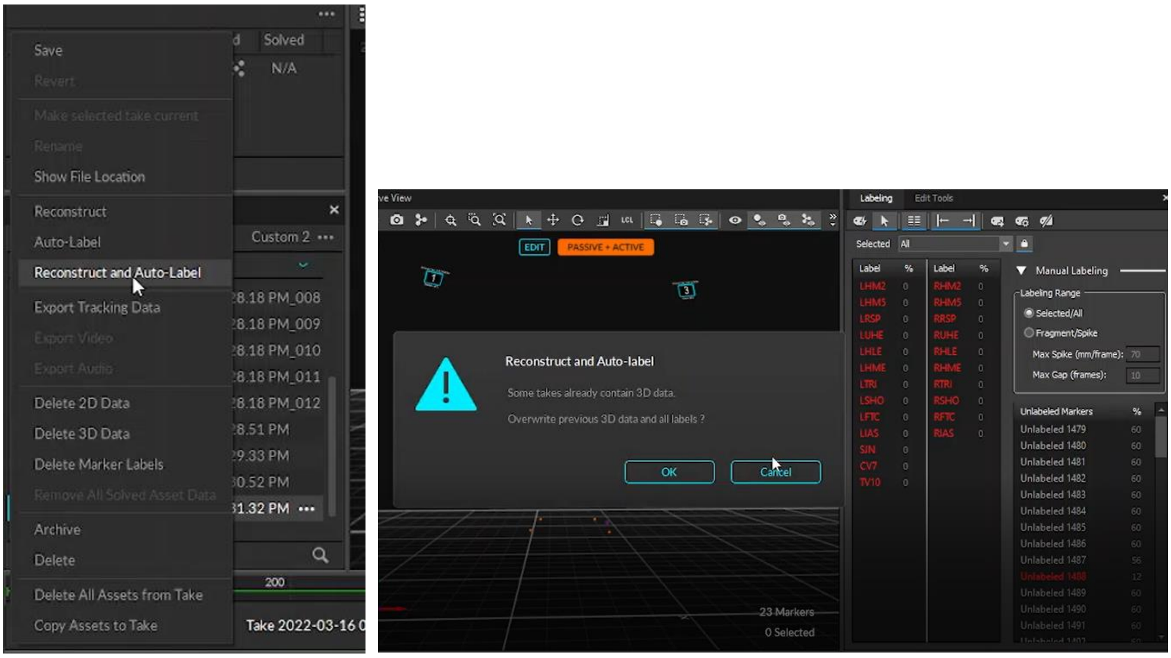

Figure 4.16. File options // Reconstruct and Auto-label [21]

Then, for each take, using the "Labeling Pane" (Figure 4.17), every marker from the take must be labeled to the marker from the marker set that corresponds. This process is quite manual. At some time, frames some of the markers get lost and have to be labeled several times.

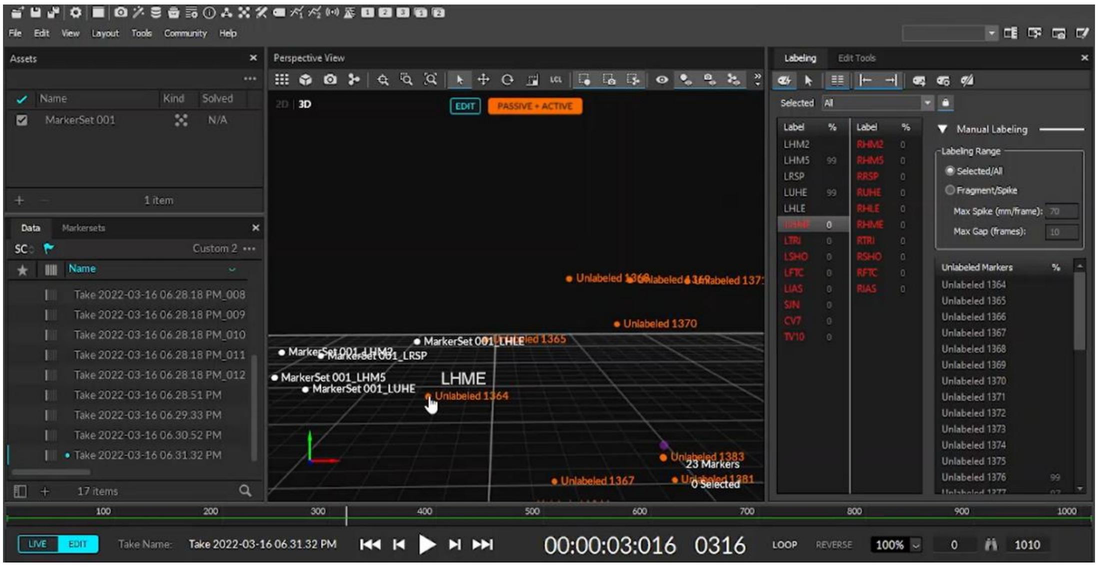

Figure 4.17. Markers assignation using Motive live mode [21]

Finally, when all "Unlabeled" markers are assigned, by using the "Edit Tools" (Figure 4.18), all-time fragments that have no information about each marker can be filled and smoothed by using the "Fill Gaps" and "Smooth" features. Then, the take is saved and the labeling is done.

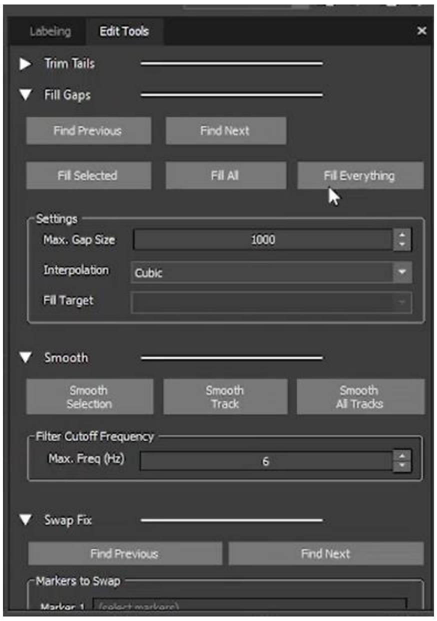

Figure 4.18. Edit Tools Pane [21]

4.2.4. Data export

The final step to do with Motive is to export the data from the takes. It exports a ".cvs" file with the position of all markers at every time frame. This file will later be converted to a ".trc" file with a Matlab code.

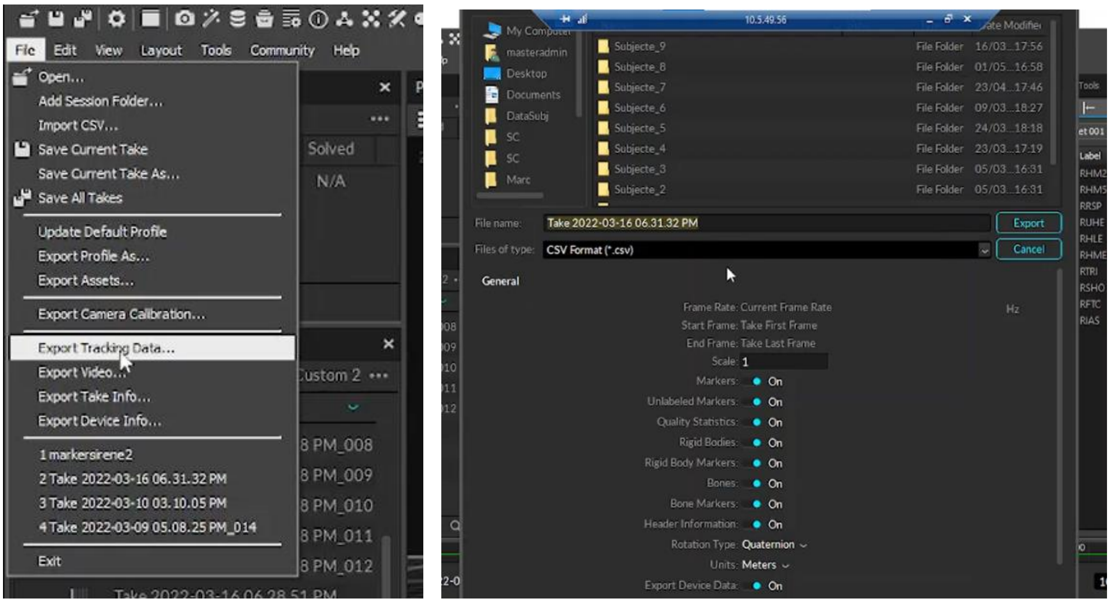

Figure 4.19. File Options // Export Tracking Data Options [21]

5. Depth camera

5.1. Real Sense D415 depth camera (Intel)

Depth cameras project infrared light onto an object, in this case onto the subject, and use the sensors to get the images [22]. Depth cameras get the position of the joints based on the distance of each joint from the camera by using infrared light. The depth camera used for this project is the Real Sense D415 from Intel (Figure 5.1) (Intel, Santa Clara, CA, USA).

Figure 5.1. Real Sense D415 Depth Camera- Front // Back [23]

5.1.1. Camera specifications

This is a model [23] that has good precision and accuracy, a focused field of view, and an RGB sensor. It is a small and light camera, easy to install and use. It can be placed on a table held by a small tripod. It has a price of 259€.

<u>-Features:</u>

·**Use environment:** Indoor/Outdoor

·**Image sensor technology:** Rolling Shutter

·**Ideal range:** 0.5 m to 3 m

<u>-Depth:</u>

·**Depth technology:** Stereoscopic

·**Minimum depth distance (Min-Z) at max resolution:** ~45 cm

·**Depth Accuracy:** <2% at 2 m1

·**Depth Field of View (FOV):** 65° × 40°

·**Depth output resolution:** Up to 1280 × 720

·**Depth frame rate:** Up to 90 fps

-RGB:

·**RGB frame resolution:** 1920 × 1080

·**RGB frame rate:** 30 fps

·**RGB sensor technology:** Rolling Shutter

·**RGB sensor FOV (H × V):** 69° × 42°

·**RGB sensor resolution:** 2 MP

-Major Components:

·**Camera module:** Intel RealSense Module D415

·**Vision processor board:** Intel RealSense Vision Processor D4

-Physical:

·**Form factor:** Camera Peripheral

·**Length × Depth × Height:** 99 mm × 20 mm × 23 mm

·**Connectors:** USB-C* 3.1 Gen 1*

·**Mounting mechanism:** – One 1/4-20 UNC thread mounting point.

– Two M3 thread mounting points.

5.1.2. Placement of the device

The depth camera has to be placed where it captures the subject's full body. In this case, it must capture the upper limbs of the body. The camera was placed on the table in front of the computer focusing on the subject.

5.2. Nuitrack

The computer program used to record the data from the depth camera is an application created as a research project [24] to improve physical rehabilitation for patients who have suffered a stroke.

5.2.1. General concepts

The application has different exercises and games to practice rehabilitation movements for patients to recover physical capacities. The application is available in English, Catalan, and Spanish. As can be seen in the following screenshots, it has a simple appearance and clear instructions. As it was done for patients to access it at home, it had to be accessible for everyone.

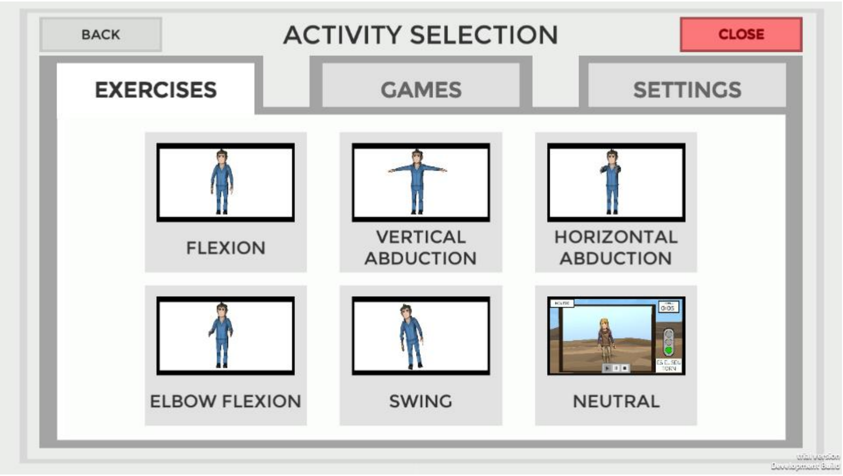

Figure 5.2. Exercises page [21]

Figure 5.3. Games page [21]

5.2.2. Neutral tool

The tool that is been used is the neutral exercise, which only shows the subject on the screen and allows to record the movements.

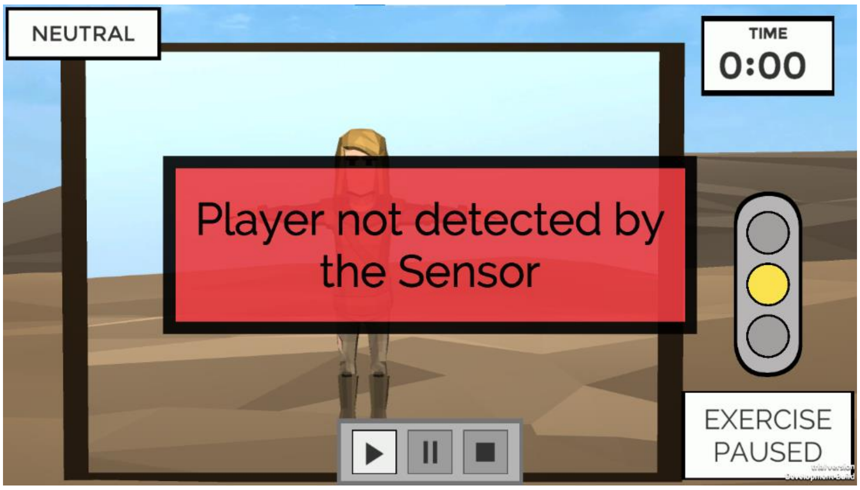

Figure 5.4. Neutral exercise page from Nuitrack [21]

Once each exercise is recorded, it is automatically saved as a ".txt" file, which later will be processed by a Matlab code to obtain the joint angles.

6. Methodology

The project has followed a schedule that has differed a little from the original idea. The Gantt chart with the tasks is included in Appendix A (Figure A.1).

6.1. Research and preparation part

The first task to be done was to get all the information needed to learn how the optical camera system and depth camera had to be placed, how to connect them to the computer, and their general performance. Second, it was necessary to get familiarized with the applications to be used, mainly the Optitrack program Motive, which had not been used before.

Once the hardware and software part were properly learned, the next assignment was to decide a set of movements to be recorded. The movements had to be activities of daily life (ADLs) with a rehabilitation component. Also to decide what marker set model to follow.

Meanwhile, another task to be done in this phase was to construct the Ground Calibration tool, which is necessary to adjust the ground in the program to the ground in reality. This was done with the help of another student, Francesc Serrate, who had a 3D printer at home.

6.2. System assembly

The following steps to be performed were to place the cameras of the optical camera system where the best images could be obtained. Then, as the light from outside was bringing reflections to the cameras, the windows of the lab were covered. Next, the light from the ceiling light also produced reflections, so it was also covered. As the subject was going to be sat right in the middle of all 6 cameras, the depth camera also had to be situated at the correct place which would record the subject correctly.

6.3. Subject captures

6.3.1. Search of subjects

Several people from EEBE were reached out to become volunteers to capture their movements with both depth camera and optical camera systems. Few of these people came to the SIMMA Lab on different days and it was possible to record nine subjects. The names of the subjects remain anonymous to protect their privacy, but their age, sex, weight, and height were written down for scaling and statistical purposes. To obtain the best captures possible, the subjects had to come in adjusted clothes and take off any reflecting objects or accessories such as watches, necklaces, bracelets, etc.

6.3.2. Markers model

The markers model that has been followed is an adapted version of a model from a research paper [25]. The markers (Figure 6.1) used from the paper and their location are:

- HM2: At the end of the second Metacarpus
- HM5: At the end of the fifth Metacarpus
- RSP: At the Carpus, next to the beginning of the first Metacarpus
- UHE: At the Carpus, next to the beginning of the fifth Metacarpus
- HLE: At the Humeral Capitulum
- HME: At the Humeral Trochlea
- SAE (SHO in this project): At the Shoulder
- IAS: At the Anterior Superior Iliac Spine
- FTC: At the Greater Trochanter of Femur
- TV10: At the tenth Vertebra, at the Thoracic
- SJN: At the middle of both Clavicles
- CV7: At the seventh Vertebra, at the Cervical

Then, another marker has been added to provide better captures. This marker (TRI) goes at the middle of the humerus, on the triceps.

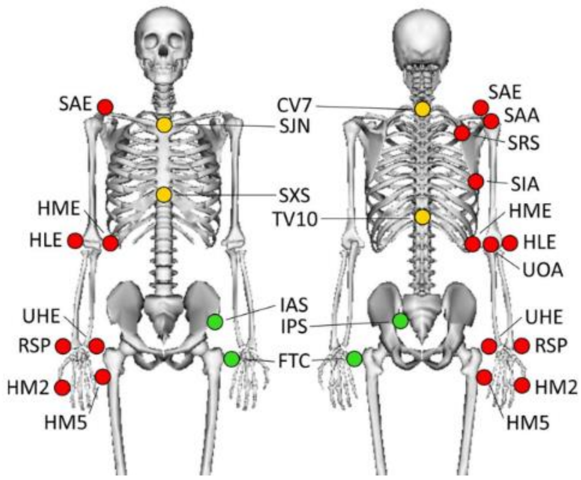

Figure 6.1. Markers set model [24]

6.3.3. Movements

There were two types of captures: a static capture and eleven dynamic movements. During all captures, the subject had to be sat on a stool that was put previously in place. The first capture was the static position. This consists of standing maintaining the arms in a T position sitting on the stool. The static capture was necessary to scale the model later with OpenSim. We recorded for approximately 10 seconds.

The dynamic movements work a little bit differently. At the beginning of each capture, it was necessary to do the synchronization movement: three iterations moving the right hand up and down. Then the corresponding movement started and it was repeated 5 times. The movements chosen [5] are a mix of daily life and aerobic exercises.

- **Greet**: Right-arm 90º up and rotate to the left 90º.
- **Drink water**: Hand on the chair (to the marks) up to the face.
- **Move an object from one box to another**: The boxes must be on the marks on the chair, and the participant moves the small plastic balls with both hands from one box to another.
- **Move a box:** Without holding a box, with hands with the palms inside and go up and down with straight arms 90º; from 45º to 135º
- **Pass pages from a book**: the initial position has both hands on both legs, the left hand looking down and the right hand 90º vertical. The left-hand stays still while the right hand rotates from the initial position to being upside down right next to the left hand. The right hand must not go on top of the left hand.
- **Comb**: Without holding any hairbrush, simulate the action of combing with the right hand while the left-hand stays still on top of the left hand.
- **Brush teeth:** With the arm at 90º from the vertical coordinate, it inclines until it goes in front of the mouth, simulating brushing teeth.
- **Rotate a stick:** With both hands at the marks, the subject rotates in circles clockwise.
- **Vertical abduction:** 180º up and down.
- **Horizontal abduction:** 90º from in front to a T position.
- **Flexion-extension:** With the arm in horizontal 90º up and down.

6.3.4. Sequence

For every subject that was recorded a sequence of steps were followed:

1) The subject had to take off all reflecting objects and note their age, sex, weight, and height.
2) All markers were placed in their proper place on the subject.

3) The subject went to the recording position.
4) The static capture, for scaling, was recorded.
5) The rest of the captures of the movements were recorded.
6) The subject took off the markers and it was all done.

After a recording session was done, all captures were saved in their corresponding folder in a systematic way to streamline data processing.

6.4. Data processing

6.4.1. Motive

The application Motive is the software tool necessary to record and process the captures with the optical camera system. In the 4.2 section, there is a more detailed explanation of how Motive works.

6.4.2. MATLAB

The MATLAB application has mainly been applied in automatizing data processing. It has been used for different purposes. The detailed codes can be found in Annex B. The first code "write_trcfile.m" converts the CVS file that we obtain with the tracking data information from Motive to a TRC file which will be subsequently processed by another code. The second code "findSyncroDepth.m" finds the delay between the capture from the optical camera system and the depth camera. The code "SyncroAndKin.m" takes the files to be synchronized and, using the "findSyncroDepth.m" code synchronizes both files and at the end creates the ". mot" file with the "write_motionFile.m". Finally, both files are processed by the code "getKinematics.m", which is a function to calculate the joint angles from the OpenSim model created previously.

6.4.3. OpenSim

The OpenSim application was used to create a model for each subject and obtain the joint angles with Inverse "Kinematics Tool" [26]. First, to ease the process, an already existing model was modified to having only the upper limbs of the skeleton, and then scaled for each subject using the "Scaling Tool" (Figure 6.2. OpenSim Scaling Tool screenshot). The scaling was done with the static captures from the optical camera system. After scaling the model, the skeleton from OpenSim (Figure 6.2) should be in a T position, like the static capture (Figure 6.3). The scaling tool reads the data of the markers from the static capture done by the optical cameras and adapts the generic model of OpenSim to a model that corresponds to the height and weight of the subject. It associates pairs of markers that will define the different joints of the model. This has to be done for all subjects because every subject is different, and the model needs to correspond to each subject, otherwise, the inverse kinematics would not provide correct values.

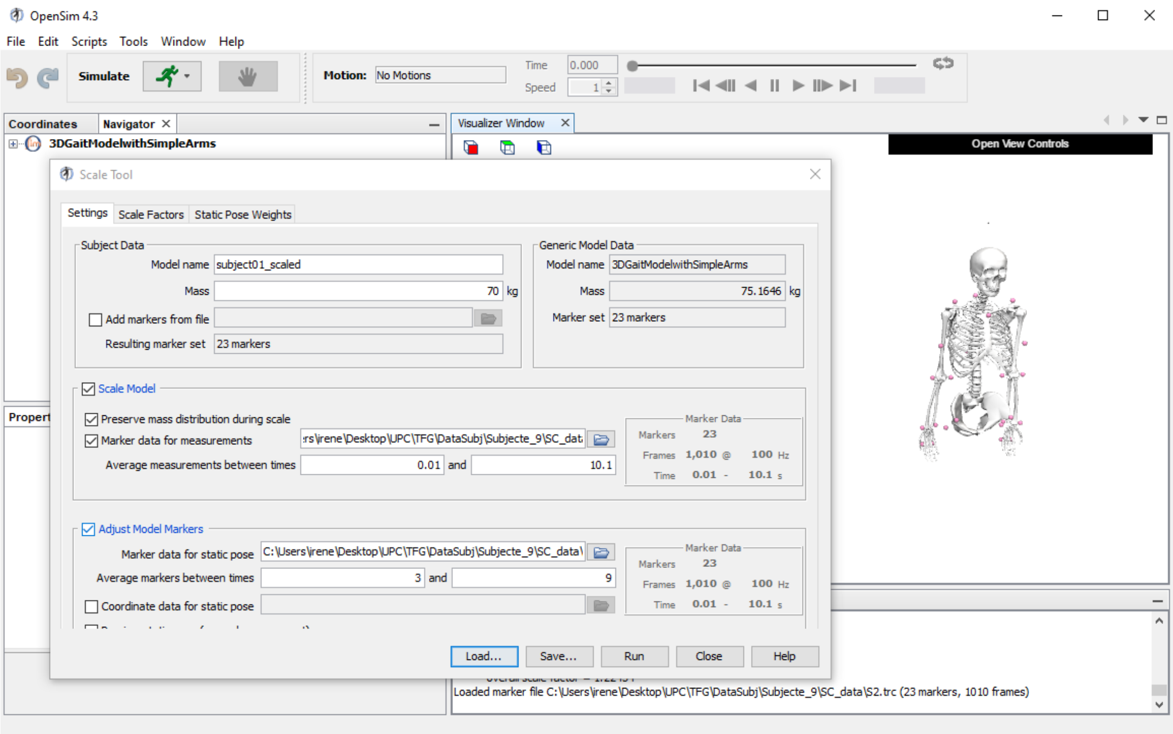

Figure 6.2. OpenSim Scaling Tool screenshot [21]

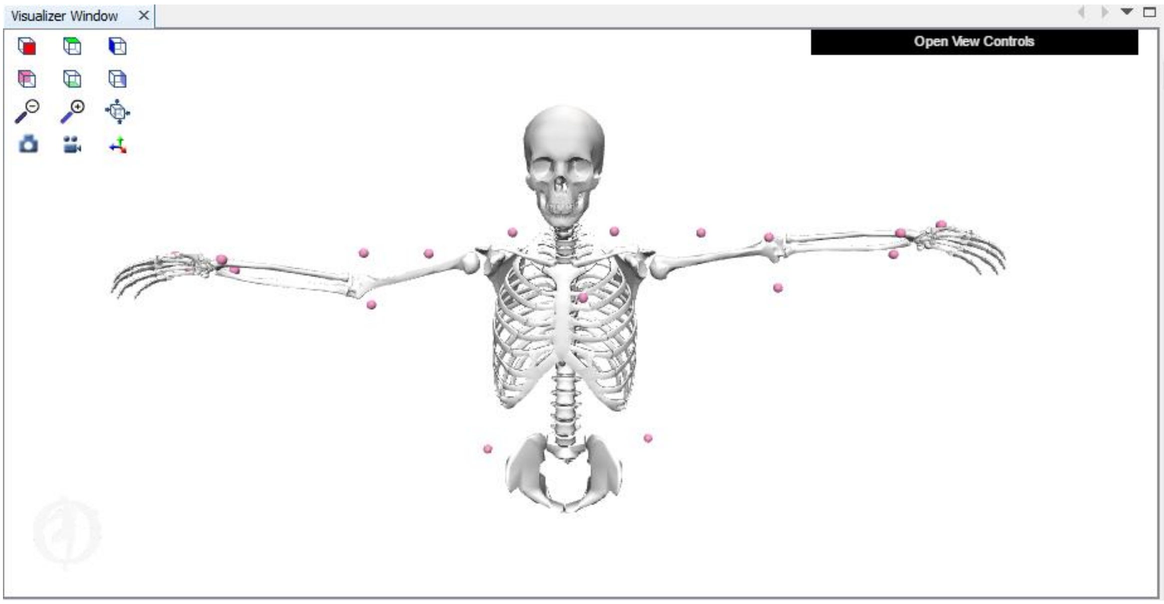

Figure 6.3. Scaled model of OpenSim [21]

Once the scaling is done, each motion file that has been obtained with the "getKinematics.m" Matlab function is loaded, and the Inverse Kinematics Tool (Figure 6.4) is executed to obtain the joint angles. The Inverse Kinematics tool of OpenSim provides a motion file with its corresponding joint angles. This motion file can be executed by OpenSim, showing the movement, the movement should correspond to the real movement done by the subject.

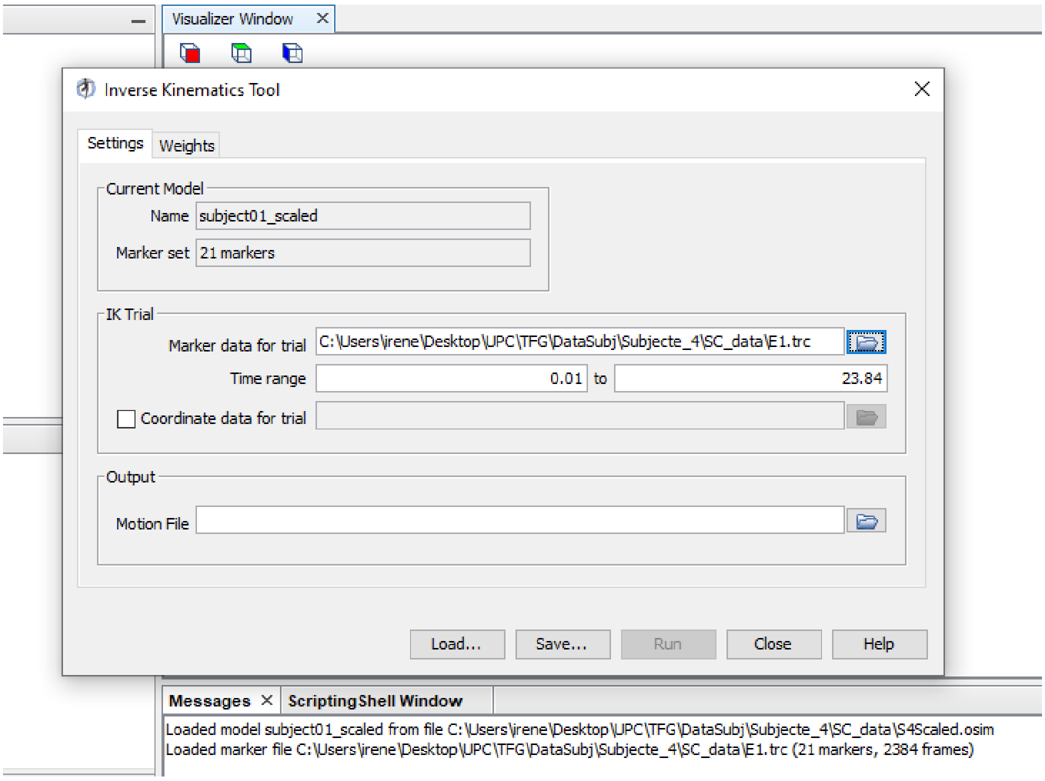

Figure 6.4. Inverse Kinematics Tool of OpenSim [21]

The motion file obtained with the Inverse Kinematics tool with de data from the optical cameras is the file from which a plot and a comparison can be made with the data from the depth camera. The motion file is saved as a '. mot' file.

7. Results

To obtain the results of the joint angles two methods were used. The first one with OpenSim with the data from the optical cameras, and the second one, with a Matlab file with the data from the depth camera. To show the results with the different methods the plots of the data from both systems are compared.

7.1. Inverse Kinematics by OPENSIM (Optical Camera System)

The motion file obtained with the Inverse Kinematics tool of OpenSim are plotted, these plots represent the angles of each joint of the data obtained from the optical cameras. Some angles maintain their value during the time interval of the exercise, this angles are mainly lower extremities or joints that are maintaining its position its position during the movement.

7.2. Inverse Kinematics by MATLAB (Depth Camera)

The data recorded by the depth camera is stored as '.txt' files, these files are read with the Matlab file 'SyncroAndKin.m'. The Matlab file calls a function, calculates the joint angles using the joint coordinates position data from the depth camera, and brings back a motion file ('. mot'). Every motion file corresponds to an exercise and it is opened with OpenSim on the corresponding scaled model of the subject. The motion files obtained should represent the real movement done by the subject. Once it was checked that the motion file represents a correct movement, the joint angles are plot the same way as the ones obtained by the optical cameras.

7.3. Comparison of the results by the two methods

The following figures show the angles of the relevant joints of the two systems from the movement 1 and subject 4. For each angle the plot at the left side represents the values of the joint angles of the data from the optical cameras, and the plot at the right side represents the values of the joint angles of the data from the depth camera.

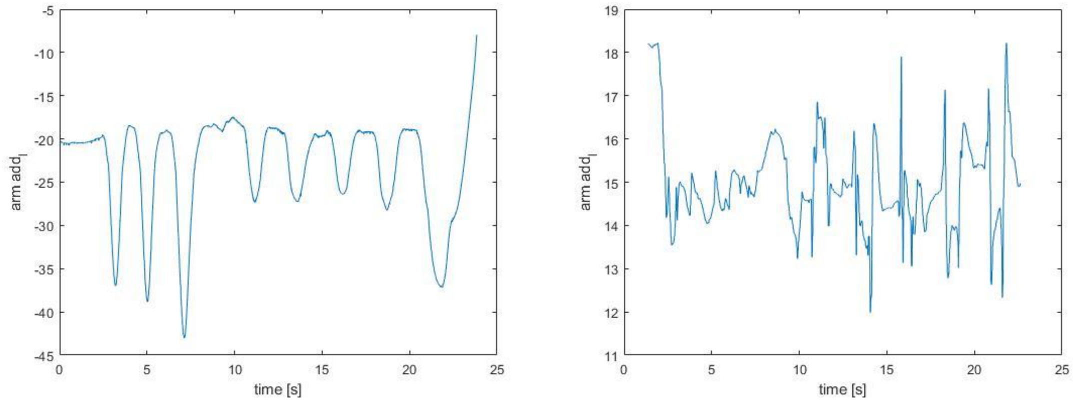

Figure 7.1. Left arm abduction angles with the optical cameras (left) and the depth camera (right)

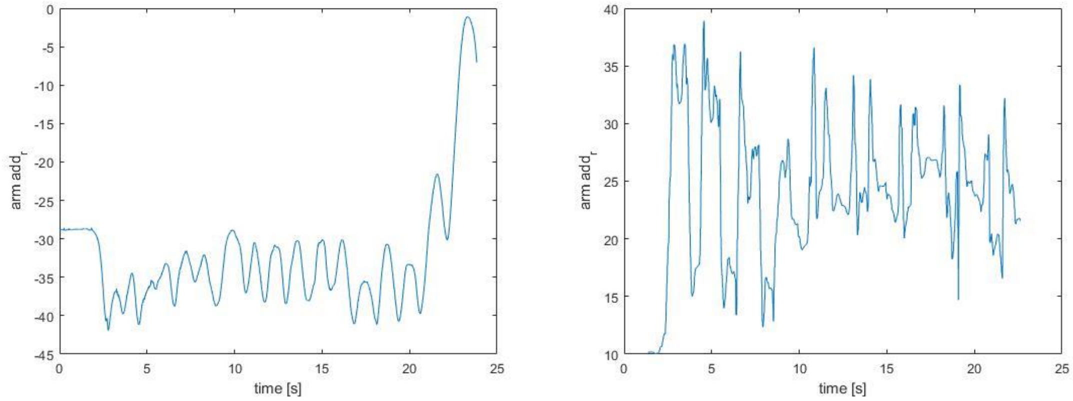

Figure 7.2. Right arm abduction angles with the optical cameras (left) and the depth camera (right)

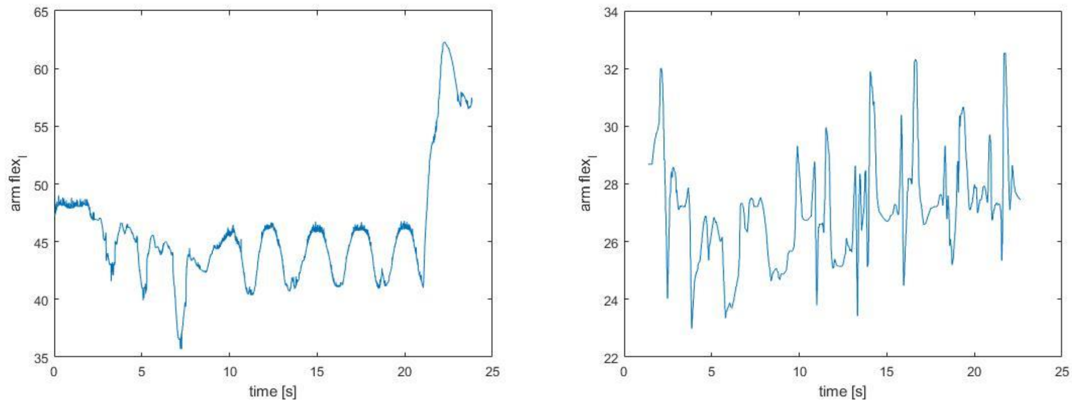

Figure 7.3. Left arm flexion angles with the optical cameras (left) and the depth camera (right)

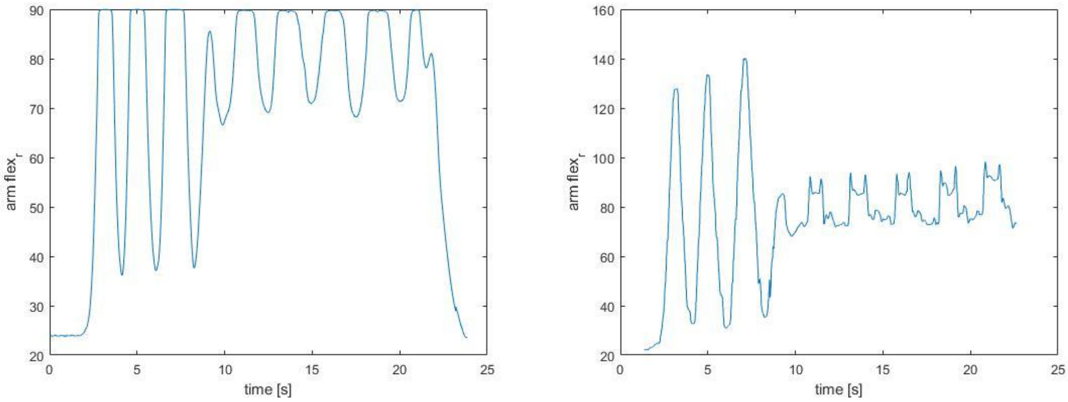

Figure 7.4. Right arm flexion angles with the optical cameras (left) and the depth camera (right)

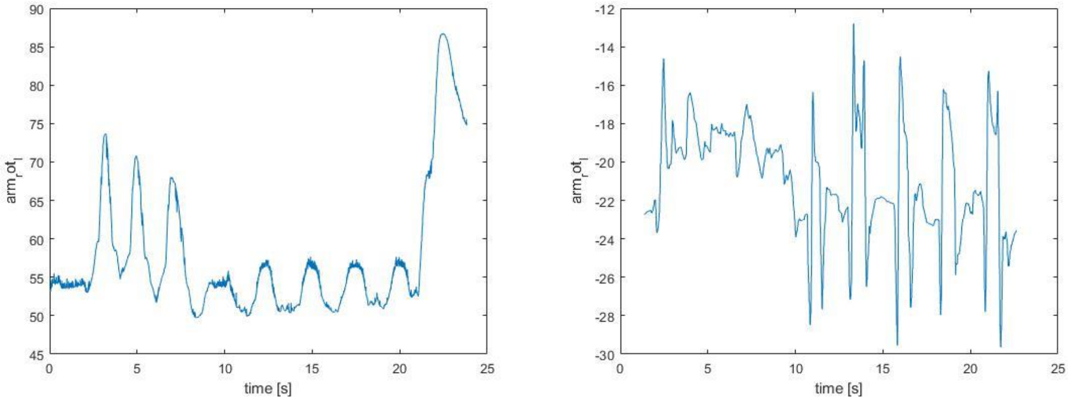

Figure 7.5. Left arm rotation angles with the optical cameras (left) and the depth camera (right)

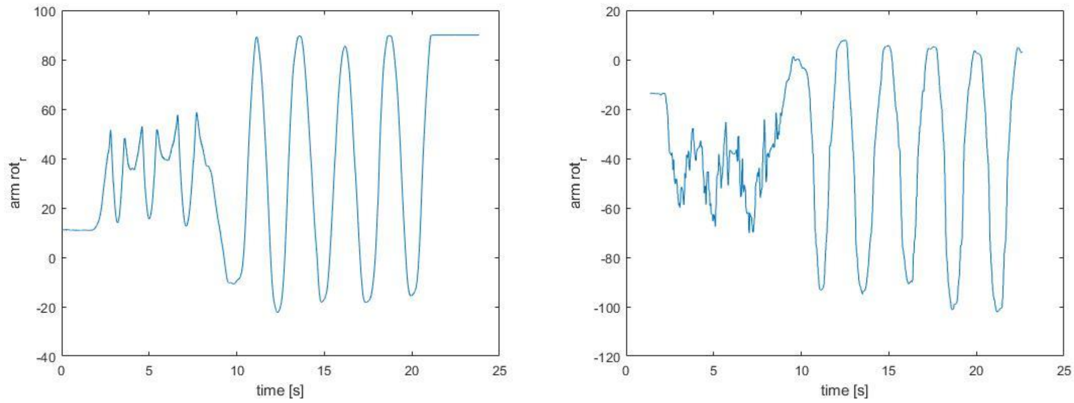

Figure 7.6. Right arm rotation angles with the optical cameras (left) and the depth camera (right)

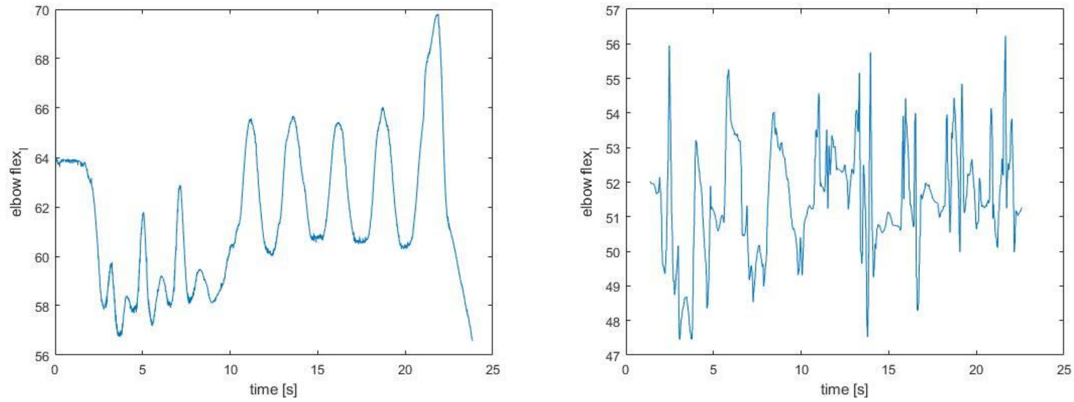

Figure 7.7. Left elbow angles with the optical cameras (left) and the depth camera (right)

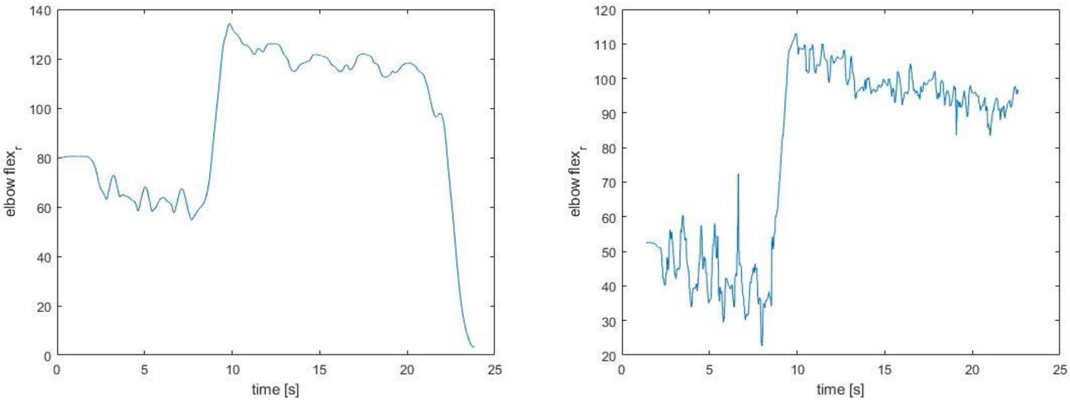

Figure 7.8. Right elbow angles with the optical cameras (left) and the depth camera (right)

The arm flexion (Figure 7.3, Figure 7.4) plots are alike for both systems for both arms, even the values of the angles are not the same, the pattern of the angles is very similar. The arm rotation (Figure 7.6) and elbow flexion (Figure 7.8) have similar patterns for both types of cameras for the right arm, the left arm (Figure 7.5, Figure 7.7) of both angles shows two plots that are very unlike. The arm abduction (Figure 7.1, Figure 7.2) do not even have similar patterns for neither right or left arm.

Environmental Impact Analysis

The environmental impact of this project is very low due to two main reasons. First, the project was performed mainly online, staying at home and only having to go to the lab for the first month. Second, because the materials used were few electronic devices, which have a low impact on the emissions of CO2.

In fact, not only has very few CO2 emissions but the application of this thesis supposes a reduction of CO2 emissions. This is because its application improves telerehabilitation, which reduces the displacement of the patients to the hospital.

One of the impacts that this project may have is due to the electronic devices. Electronic devices are very difficult to recycle and this causes an environmental impact. This is regulated by the European Directive 2012/19/UE [27].

The other factor that produces an impact is the displacement from home to the university work at the lab. During the project, it has been necessary to go from El Vendrell to the EEBE approximately 25 times. The journey is done by car, train, metro, and walk. The three methods of transport have 3 different CO2 emission factors, so we can calculate separately the emissions of CO2 of each. The emissions are calculated by multiplying the CO2 emission factor [28] and the distance of the journey.

Transport	CO2 Emission Factor[26] [**¡Error! Marcador no definido.**] (g CO2/km)	Distance (km)	CO2 emissions (g CO2)
Car	121	8,1	980,1
Train	33	65	2145
Metro	30	5,6	168
TOTAL	-	78,7	**3293,1**

Table 0.1. CO2 emissions calculation table

The total value of CO2 emissions of every journey was 3.293,1 g CO2. As this journey was done approximately 25 times the total emissions were 82.327,5 g of CO2.

Conclusions

The initial aim of this project was to compare the results of kinematic and dynamic analyses with both motion capture systems used, an optical camera system and a depth camera. The main goal was to prove by both methods that the quality of the data recorded by depth cameras could be as accurate as the data from an optical camera system. Since depth cameras are way cheaper than optical camera systems, the idea was to prove that it is possible to perform rehabilitation therapies and keep track of the improvements of the patient without having to do any visits to the hospital.

As the project started from zero, having to learn how all the computer programs worked and not knowing all the complications that we were going to find, it took months to get any takes correctly processed. Also, it was the first time at the lab that optical cameras and a depth camera were used at the same time, and that the data from both systems were compared, which led to several drawbacks. Due to time constraints, this project has ended up being more focused on documenting all the information about the performance of the computer programs and the issues that may appear and potential solutions when using both camera systems simultaneously. The idea is to provide a guide to ease further research work.

First, nine subjects were recorded doing the different movements with both optical cameras and depth cameras. The markers that were on the joints were easy to place on the subjects because the exact point where they had to be was clear. The markers on the pelvis and the triceps were more difficult to put correctly because it was not clear the exact point where they had to be put. Another conclusion is that the number of markers on the subjects (23) was not enough, more markers would have supposed more time for the labeling but it would have provided more information and a more accurate scaling of the subject. This led to a scaling of the subjects that were not completely accurate. For further research, I would recommend putting more markers and putting the most of them on the joints or points that do not vary much from one subject to the other. I would also recommend using a T-shirt (or several T-shirts of different sizes) with the markers fixed to it, as some markers fell during the recording sessions. The fixation of the cameras on the ceiling in SIMMA Lab will improve the motion capture session. This way the cameras will remain exactly in the same position for all takes. The acquisition from EEBE of a new Optitrack system, together with the force platforms, will allow complete dynamics analyses.

It was the first time that the depth camera and the optical cameras were used at the same time. They were executed with the same computer, which caused performance issues, potentially due to buffer limitations. Having both camera systems connected to the same computer produced noise in the data recorded with the optical cameras. This made the labelling process slow because there were many "imaginary" markers (markers that do not exist but appear in the images). A solution to this could be to use two independent computers to record with both systems, then the computers will work better and the problems caused by one of the systems would not affect the other system.

All the movements recorded were only for the upper limbs, the subject was sat on a stool. This caused some markers to get lost during the recording of the takes, especially the markers on the pelvis (IAS and FTC). The depth camera also had issues related to the position of the subject, because the joints of the lower limbs were not correctly detected, and in some takes, they seem to have movement, even though the subject did not move their lower limbs. To solve this, the subjects could do the same movements standing up, this would make the markers more visible and the depth camera would not have any problem detecting the joints of the lower limbs.

Some articles use depth cameras or optical camera systems, and inverse kinematics for motion calculations or improvements. There is an article [29] that uses the motion captured by a depth camera with a humanoid robot, it has got joint angles results that are more accurate to the real movements. Another article [30] uses also inverse kinematics with de data from a Kinect camera, this article identifies the movement of the arm and hand to develop an interface system between a robotic arm and the person’s movements. Concerning optical camera systems, there is an article [31] that uses inverse kinematics techniques to perform a skeletal parameterization and reconstruction to avoid the loss of the markers during the motion capture.

This project provides key information for any further research. It has obtained preliminary data to perform a research study, and potential issues have been identified. This report also explains the steps to follow to obtain better data from both systems, especially during the labelling process, where even a video tutorial was done to ease the process.

In conclusion, the initial idea of this project was to prove that depth cameras are reliable enough to record data with enough accuracy, as the optical cameras system does. Because of the complications that were found, it has finally been a project that explains the process and provides a guide for further research work to get more accurate data and be able to prove what initially was meant to prove.

Budget and Economic Analysis

The economic analysis of a project of this kind is based on the costs of the project. The costs of this project have been divided into three principal groups: Software, Hardware, and personnel costs. Then, the total costs are the sum of the costs of both groups.

For either software or hardware, the project has used them for only a period, and the rest will stay at the lab for other uses and projects. So, the real cost of them applied to the project is calculated by their depreciation, which is calculated by the following equation (Equation 0.1):

$$real\ cost(€) = adiquisition\ cost(€) * \frac{time\ of\ use\ (months)}{service\ life\ (months)} \qquad \text{[Equation 0.1]}$$

Software costs

We consider as software all computer programs that have been used for the project. In the table below (Table 0.1) there are all software costs detailed:

Software	Cost	Units	Time of use (months)	Service life (months)	Real cost
Motive [29]	2.499€	1	4	12	833,00€
OpenSim [30]	0*	1	4	12	0
Nuitrack [1]	59,90€	1	4	12	19,97€
TOTAL	-	-	-	-	**853,00€**

Table 0.1. Software costs

*OpenSim has no cost because it is an open-source software.

As the table (Table 0.1) shows, the total cost of software is 853€.

Hardware costs

We consider hardware all the devices used for this project. The computer and all the material that was already in the lab that is not specific for this project were not taken into account. The same happens with the laptop or the material from home (papers, pencils, etc.). In the table below (Table 0.2) there are all hardware costs detailed:

Hardware	Cost	Units	Time of use (months)	Service life (months)	Real cost
Optical Flex 3 [3]	659€	6	4	12	1.318€
Optihub 2 [8]	329€	2	4	12	219€
USB cables [31]	10€	7	4	5	56€
High tripods [32]	100€	4	4	5	320€
Medium tripods [33]	50€	2	4	5	80€
Low tripods [34]	20€	1	4	5	16€
PC	1500€	1	4	96	62,5€
Laptop	450€	1	4	60	30€
TOTAL	-	-	**-**	**-**	**2.101,5€**

Table 0.2. Hardware costs

As the table (Table 0.2) shows the total hardware cost is 2.009€.

Personnel costs

The personnel costs are calculated with the salaries of two engineers, who represent the author and the tutor of this project.

Personnel	Salary	Period of time at the project	Real cost
Biomedical Engineer [35]	27628 €/year	4	9.209,33€
Mechanical Engineer [36]	30458 €/year	4	10.152,67€
TOTAL	**-**	**-**	**19.362,00€**

Table 0.3. Personnel Costs

As the table (Table 0.3) shows, the total personnel cost is 19.362€, this represents the main cost of this project.

Total costs

The total cost is the sum of both software and hardware costs. The table below (Table 0.4) resumes the costs:

Category	Cost
Software	853,0€
Hardware	2.101,5€
Personnel	19.362,0€
Total	**22.316,5€**

Table 0.4. Total costs

In conclusion; the total cost of this project is 22.316,5€.

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A. Appendix A. Project Organization

The project has had a total duration of 22 weeks. It started in the middle of December and finished at the beginning of June. To show the duration of the different tasks during the five months a Gantt Chart (Figure A.1. Gantt chart of the project) was created.

ACTIVITY	PLANNED START WEEK	PLANNED DURATION	REAL START WEEK	REAL DURATION
Work planning	1	1	1	2
Initial research	2	2	3	2
Learning about the computer programs	3	3	4	2
Familiarization with the computer programs	4	3	5	4
First tests with the optical camera system	5	1	6	1
First tests with the depth camera	6	1	7	1
Hardware problems solving	5	1	5	3
Final tests with both camera systems	6	1	7	1
Exercises and movement research	5	2	5	2
Markers research	5	2	6	1
Subject research	5	1	6	2
Subjects exersices recording	7	4	8	6
Data Organization	11	1	12	2
Labelling	11	3	12	6
Data Processing	14	4	18	4
Research and information collection	8	6	8	8
Report writing	12	8	15	8

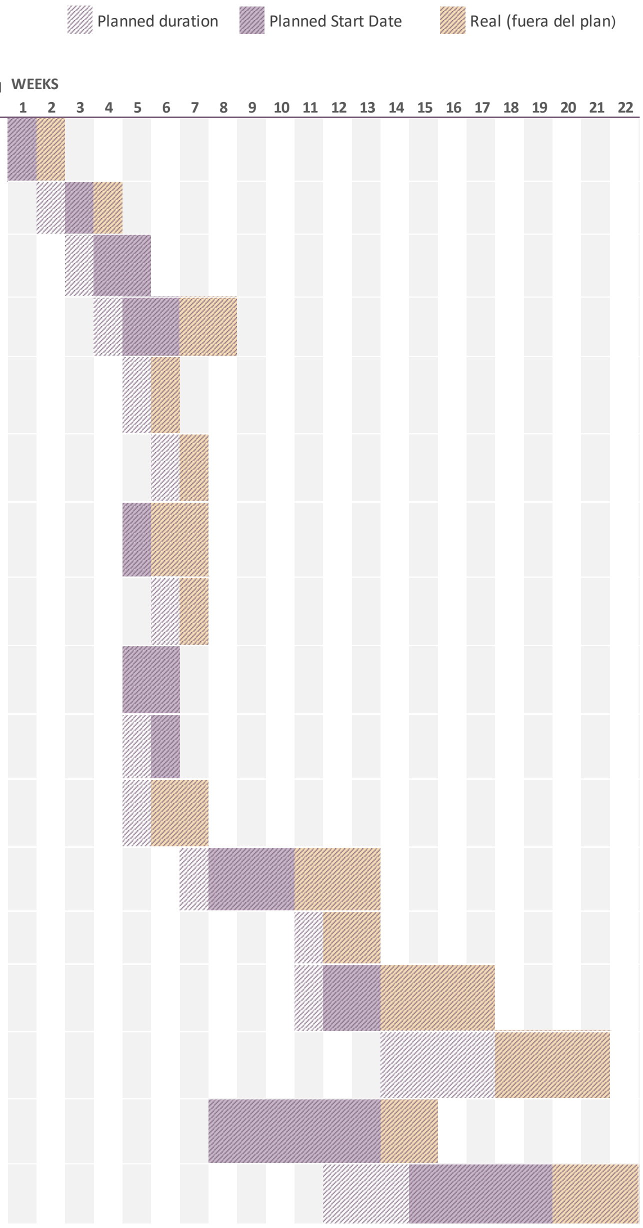

Figure A.1. Gantt chart of the project

B. Appendix B. Movements

In the following, the main images of the movements captured are presented. All the images are screenshots of the videos taken in one subject.

Static movement

Figure B.1. Static movement

Synchronization movement

Figure B.2. Synchronization movement (done in all takes before the movement)

Greeting

Figure B.3. Greeting movement

Drink water

Figure B.4. Drink water movement

Move an object from one box to another

Figure B.5. Move an object from one box to another movement

Move a box

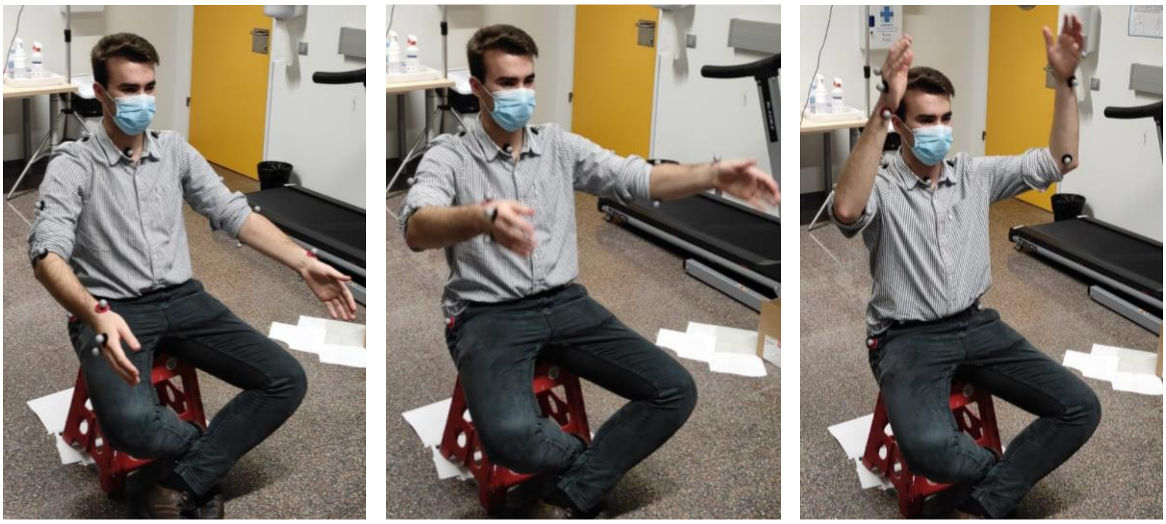

Figure B.6. Move a box movement

Passing pages from a book

Figure B.7. Passing pages from a book movement

Combing

Figure B.8. Combing movement

Brushing teeth

Figure B.9. Brushing teeth movement

Rotating a stick

Figure B.10. Rotating a stick movement

Vertical abduction

Figure B.11. Vertical abduction movement

Horizontal abduction

Figure B.12. Horizontal abduction

Flexion-extension

Figure B.13. Flexion-extension movement

C. Appendix C. Matlab Codes

Write_trcfile

The optical camera system provides a .cvs file with the coordinates of each marker but to perform the needed calculations in OpenSim we need a .trc file. To convert the .cvs file to a .trc file the file 'write_trcfile.m' was used:

```
%write in trc file
[marker_data]=csvread('ex13.csv',8,0);
nframes=size(marker_data,1);
nframe=1:nframes;
time=0:0.01:(nframes-1)/100;
markers =
[{'CV7'},{'LFTC'},{'LHLE'},{'LHM2'},{'LHM5'},{'LHME'},{'LIAS'},{'LRSP'},{
'LSHO'},{'LTRI'},{'LUHE'},{'RFTC'},{'RHLE'},{'RHM2'},{'RHM5'},{'RHME'},{'
RIAS'},{'RRSP'},{'RSHO'},{'RTRI'},{'RUHE'},{'SJN'},{'TV10'}]; % get
markers names
nmarkers=size(markers,2);
filename='takemarkers.trc';
% first initialise the header with a column for the Frame # and the Time
% also initialise the format for the columns of data to be written to
file
dataheader1 = 'Frame#\tTime\t';
dataheader2 = '\t\t';
format_text = '%i\t%2.4f\t';
% initialise the matrix that contains the data as a frame number and time
row
% data_out = [nframe; time]';
data_out =[];
data.Start_Frame=nframe(1);
data.End_Frame=nframe(end);
data.Rate=100;
nrows=nframes;
data.units='mm';

% now loop through each maker name and make marker name with 3 tabs for
the
% first line and the X Y Z columns with the marker number on the second
% line all separated by tab delimeters
% each of the data columns (3 per marker) will be in floating format with
a
% tab delimiter - also add to the data matrix
for i = 1:nmarkers
    dataheader1 = [dataheader1 markers{i} '\t\t\t'];
    dataheader2 = [dataheader2 'X' num2str(i) '\t' 'Y' num2str(i) '\t'...
        'Z' num2str(i) '\t'];
    format_text = [format_text '%f\t%f\t%f\t'];
%     data_out=[data_out marker_data(:,(i*3-1):(i*3+1))];
end
```

```
marker_data(:,3:end)=marker_data(:,3:end)*1000;
data_out=marker_data;


dataheader1 = [dataheader1 '\n'];
dataheader2 = [dataheader2 '\n'];
format_text = [format_text '\n'];

disp('Writing trc file...')

newfilename = filename;

%open the file
fid_1 = fopen([newfilename],'w');

% first write the header data
fprintf(fid_1,'PathFileType\t4\t(X/Y/Z)\t %s\n',newfilename);
fprintf(fid_1,'DataRate\tCameraRate\tNumFrames\tNumMarkers\tUnits\tOrigDa
taRate\tOrigDataStartFrame\tOrigNumFrames\n');
fprintf(fid_1,'%d\t%d\t%d\t%d\t%s\t%d\t%d\t%d\n', data.Rate, data.Rate,
nrows, nmarkers, data.units, data.Rate,data.Start_Frame,data.End_Frame);
fprintf(fid_1, dataheader1);
fprintf(fid_1, dataheader2);

% then write the output marker data
keyboard;
fprintf(fid_1, format_text,data_out');

% close the file
fclose(fid_1);

disp('Done.')
```

SyncroAndKin

The rest of the parameters are calculated from the file 'SyncroAndKin.m' was used. This file calls different functions, that will be explained afterward.

```
depthcam_filename='CPS4E1';
opticalcam_filename='E1.trc';

%Synchronization (t0 is time to add to depth camera to get syncrhonized
data)
t0=findSyncroDepth(opticalcam_filename,depthcam_filename);

%Get Angles from depth cameras
kinematics_dc=getKinematics(depthcam_filename,t0);

%Write file
write_motionFile(kinematics_dc,'CPS4E1.mot');
```

FindSyncroDepth

When recording the movements, it was not possible to ensure that both files started recording at the same exact time. So it was necessary to synchronize the files after recording them. To do this the function 'findSyncroDepth.m' was used. This function calls the data files from both depth camera and optical camera system and provides the time lapse between the two functions. This time is later used to synchronize both files.

```
function t0=findSyncroDepth(opticalcam_filename,depthcam_filename) %time to add
to depth camera
    data_opcam=readtable(opticalcam_filename,'FileType','delimitedtext');
    colhand=find(contains(data_opcam.Properties.VariableNames,'RHM2'));
    hand_opcam=table2array(data_opcam(:,colhand:colhand+2));
    handy_opcam=hand_opcam(:,2);
    time_opcam=table2array(data_opcam(:,2));

    data_depthcam=readtable(depthcam_filename,'FileType','delimitedtext');

colhand_dc=find(contains(data_depthcam.Properties.VariableNames,'hand_r_x'));
    hand_dc=table2array(data_depthcam(:,colhand_dc:colhand_dc+2));
    hand_dc=strrep(hand_dc,',','.');
    hand_dc=cellfun(@str2num,hand_dc);
    handy_dc=hand_dc(:,2);
    time_dc=data_depthcam(:,1);
    time_dc=table2array(time_dc);
    time_dc=strrep(time_dc,',','.');
    time_dc=cellfun(@str2num,time_dc);

    %Get maximums from right hand initial 3 movements optical camera
    close all;
    figure(1);
    plot(handy_opcam);
    rect=getrect(figure(1));
    x1=floor(rect(1));
    x2=floor(rect(1))+ceil(rect(3));
    [maxs_optcam,locs]=findpeaks(handy_opcam(x1:x2)); %get maximum points
within the rectangle
    [maxs_optcam,locs]=removewronglocs(maxs_optcam,locs);
    [maxs_sort, I]=sort(maxs_optcam,'descend');
    locs_optcam=locs(I(1:3))+x1-1;
    locs_optcam=sort(locs_optcam);

    %Get maximums from right hand initial 3 movements depth camera
    close all;
    figure(1);
    plot(handy_dc);
    rect=getrect(figure(1));
    x1=floor(rect(1));
    x2=floor(rect(1))+ceil(rect(3));
    [maxs_dc,locs]=findpeaks(handy_dc(x1:x2)); %get maximum points within the
rectangle
    [maxs_dc,locs]=removewronglocs(maxs_dc,locs);
    [maxs_sort, I]=sort(maxs_dc,'descend');
```

```
    locs_dc=locs(I(1:3))+x1-1;
    locs_dc=sort(locs_dc);

    t_optcam=time_opcam(locs_optcam);
    t_depthcam=time_dc(locs_dc);

    t0=mean(t_optcam-t_depthcam);
    if std(t_optcam-t_depthcam)>1
        warning('error when synchronizing?');
    end

end
function [maxs_dc,locs]=removewronglocs(maxs_dc,locs)
    difflocs=diff(locs);
    while any(difflocs<10)
        I=find(difflocs<10);
        y1=maxs_dc(I(1));
        y2=maxs_dc(I(1)+1);
        if y1>y2
            maxs_dc(I(1)+1)=[];
            locs(I(1)+1)=[];
        else
            maxs_dc(I(1))=[];
            locs(I(1))=[];
        end
        difflocs=diff(locs);
    end
end
```

GetKinematics

Once both files were synchronized and the time displacement between both files was known, it was needed to obtain the inverse kinematics from the depth file. This is obtained calling the function 'getKinematics.m'. This Matlab function cannot be published because it is confidential.

Write_motionFile

OpenSim requires a '. mot' file to perform inverse kinematics. The function 'write_motionFile' reads the kinematics file and gives a motion file, which is later used in OpenSim.

```
function write_motionFile(q, fname)

fid = fopen(fname, 'w');
if fid == -1
        error(['unable to open ', fname])
end

if length(q.labels) ~= size(q.data,2)
```

```
        error('Number of labels doesn''t match number of columns')
end

if q.labels{1} ~= 'time'
        error('Expected ''time'' as first column')
end

fprintf(fid, 'name %s\n', fname);
fprintf(fid, 'datacolumns %d\n', size(q.data,2));
fprintf(fid, 'datarows %d\n', size(q.data,1));
fprintf(fid, 'range %f %f\n', min(q.data(:,1)), max(q.data(:,1)));
fprintf(fid, 'endheader\n');

for i=1:length(q.labels)
        fprintf(fid, '%20s\t', q.labels{i});
end
fprintf(fid, '\n');

for i=1:size(q.data,1)
        fprintf(fid, '%20.8f\t', q.data(i,:));
        fprintf(fid, '\n');
end

fclose(fid);
return;
```