



UNIVERSITAT POLITÈCNICA DE CATALUNYA  
BARCELONATECH  
Escola d'Enginyeria de Barcelona Est

FINAL DEGREE PROJECT

**Bachelor's Degree in Biomedical Engineering**

**COMPARISON STUDY OF THE LOWER-LIMB JOINT  
KINEMATICS BETWEEN AN OPTICAL SYSTEM OF  
MOVEMENT CAPTURE AND A DEPTH CAMERA**



**Report**

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## Resum

Actualment vivim en una era digital, on la presencialitat de les activitats rutinàries s'està veient substituïda a través d'una comunicació en remot, gràcies sobretot a l'internet i als mitjans i l'accessibilitat cada cop més fàcil per part dels usuaris. Alguns dels exemples més comuns poden ser tant a nivell professional (reunions, treball, classes...) com a nivell social (xats, videotrucades, xarxes socials), però hi ha altres camps que també s'afavoreixen d'aquests recursos com pot ser l'àmbit de la medicina, concretament la telerehabilitació. La telerehabilitació permet als metges i als pacients fer visites i fer un seguiment dels tractaments sense la necessitat de trobar-se presencialment.

L'objectiu d'aquest treball és analitzar la fiabilitat i precisió de l'aplicació *Telerehab*. Aquesta aplicació s'orienta a rehabilitar el moviment funcional de persones amb problemes de mobilitat, i utilitza una càmera de profunditat per capturar els moviments del pacient a nivell articular. Per a comprovar la precisió d'aquesta es va realitzar una comparativa amb un sistema de càmeres òptiques, un sistema més precís que la càmera de profunditat però alhora menys econòmic i més complex d'utilitzar. A partir d'aquí es va realitzar una valoració a nivell global.

Les captures cinemàtiques d'aquest treball s'han realitzat a les instal·lacions de la facultat de l'Escola d'Enginyeria de Barcelona Est (EEBE), concretament al Laboratori d'Enginyeria Biomèdica.

## Resumen

Actualmente vivimos en una era digital, donde la presencialidad de las actividades rutinarias se está viendo sustituida a través de una comunicación a distancia, sobre todo gracias al internet y a los medios y la accesibilidad cada vez más fácil por parte de los usuarios. Algunos de los ejemplos más comunes pueden ser tanto a nivel profesional (reuniones, trabajo, clases...) como a nivel social (chats, video llamadas, redes sociales), pero hay otros campos que también se favorecen de estos recursos como puede ser el ámbito de la medicina, concretamente la telerehabilitación. La telerehabilitación permite a los pacientes realizar visitas y realizar un seguimiento de los tratamientos sin la necesidad de encontrarse presencialmente.

El objetivo de este trabajo es analizar la fiabilidad y la precisión de la aplicación *Telerehab*. Esta aplicación se enfoca en la rehabilitación de la movilidad funcional de las personas con problemas de movilidad y utiliza una cámara de profundidad para capturar los movimientos del paciente a nivel articular. Para comprobar la precisión de este se ha realizado una comparativa con un sistema de cámaras ópticas, un sistema más preciso que la cámara de profundidad, pero a la vez menos económico y más complejo de utilizar. A partir de ahí se realizó una valoración a nivel global.

Las capturas cinemáticas de este trabajo se han realizado en las instalaciones de la facultad de la Escola d'Enginyeria de Barcelona Est (EEBE), concretamente en el Laboratorio de Ingeniería Biomédica.

## Abstract

We currently live in a digital era, where face-to-face routine activities are being replaced by remote communication, mainly thanks to the internet and media and the increasing ease in accessibility by users. Some of the most common examples can be both at a professional level (meetings, work, classes...) such as at social level (chats, video calls, social networks), but there are other fields that also benefit from these resources such as the medical field, specifically telerehabilitation. Telerehabilitation technology allows doctors and patients to make visits and follow treatments without the need to meet in person.

The aim of this work is to analyze the reliability and accuracy of *Telerehab*. This application aims to help functional mobility recovery in patients with mobility problems and uses a depth camera to capture patient's joints movement. To check the accuracy of it, a comparison was performed with a system of optical cameras, more precise than the depth camera but at the same time less economical and more complex. At this point a global analysis was carried out.

The kinematic captures of this work have been recorded in the Escola d'Enginyeria de Barcelona Est (EEBE) faculty facilities, specifically in the Biomedical Engineering Laboratory.



## **Acknowledgments**

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Finally, I would like to thank all the volunteers that came to the faculty to serve as study subjects for this project.

## Glossary

ADL - Activities of Daily Living

BEL - Biomedical Engineering Laboratory

DOF - Degrees Of Freedom

EEBE - Escola d'Enginyeria de Barcelona Est

SIMMA - Simulation and Movement Analysis

TOF – Time Of Flight

UPC - Universitat Politècnica de Catalunya



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# 1. Preface

## 1.1. Context

Since the invention of the Internet, some daily activities have changed substantially. The world's pandemic which we are currently living in has exposed the evolution of this technology demonstrating that virtual activities such as work, classes or meetings among others can be done without the need of having to be face-to-face. Although some activities still demand this physical presence (and probably always will), virtual work offers a lot of advantages. The ease of meeting with someone else, reduction in time and transport costs are some of them.

Medicine has also experienced some changes and improvements in its way of working. Nowadays, the *Da Vinci* (Intuitive Surgical, Sunnyvale, CA, USA) allows a doctor to do surgical operations far from the surgical room, and x-rays and scanners can be analyzed by any doctor in the world thanks to global networks. Telerehabilitation is a type of treatment or rehabilitation that can be done virtually without the necessity to move around.

## 1.2. Origin of the project

This project is part of a bigger project that has been carried out by different scientists assigned to the UPC, consisting of the creation of an application that helps the rehabilitation of people who have suffered a stroke and have lost cognitive and motor abilities [1].

The task of this project was to record the movement of different people focusing on the lower limb joints with two different motion capture systems (the depth camera with comparison to the optical camera system) and to analyze and compare one with the other. More precisely, the comparison was based on the difference in the angles and moments of the leg joints. The movements were performed on top of a force plate to have more information about forces and power supporting the captures to be able to do a more accurate comparison. So there was three different equipment providing three different data sources.

### 1.3. Motivation

Since I started the biomedical engineering degree, I have always been attracted to mechanical forces and equilibrium, moments, biomechanics, and efficiency of the movement. When it came to choose a subject for my final degree project, I was sure I wanted to do it on a biomechanical matter, and I found Gil's proposal of being part of this project very interesting because of the possibility to contribute to the scientific field and to work in the Simulation and Movement Analysis (SIMMA) laboratory with some complex equipment such as the optical cameras.

## 2. Introduction

It has been noticed that, besides the surgical intervention, patient treatments and long-term monitoring in chronic diseases are a big economic charge in the medical field. Telemedicine has proved to contribute to medicine in many ways: diagnostic and monitoring, early risk detection, treatments and rehabilitation and provision of feedback alerts. Its clinical and cost effectiveness is undeniable not only for its direct effect on the treatment, being more autonomous, but also because of the early detection of symptoms thanks to the information it provides that can translate in a more economic clinical intervention.

This innovative model of healthcare has a lot of potential and lately, different technologies such as e-health applications, biomedical sensors and devices and integrated platforms are being used for the management and rehabilitation of diseases like stroke, dementia or cardiovascular diseases [2].

The increase of the use of telerehabilitation is accompanied with the need for accurate, low-cost and portable capture systems that can be easily used by the patients. Using a single depth camera for motion capture has proven to be cost effective compared to most of the optical systems in the industry, without compromising on accuracy [3].

### 2.1. Objectives

#### 2.1.1. Main objective

The main goal of this project is to evaluate the accuracy of the depth camera by comparing it to the optical cameras, a more complex and expensive system. A deep evaluation will be needed to understand and evaluate the accuracy price ratio.

#### 2.1.2. Specific Objectives

- Learn how the different equipment works
- Learn how the programs used work
- Capture multiple movements resembling activities of daily living to have enough data for the study

- Write the codes needed for any purpose that appears during the project, such as recording data, synchronization of the data between the different cameras and force plate and to do the comparison
- Compare the two motion capture systems in a kinematic level, according to the chosen parameters
- Do an objective comparative analysis following the chosen parameters, on the one hand regarding the accuracy and mechanical side and on the other hand the economic part

## 2.2. Scope

As mentioned, this project is part of a long-term project and aims to make a contribution to it. The scope of the work is limited to evaluate the accuracy of the depth camera (and in consequence the accuracy of the application).

The available resources for this work are all the equipment, rooms and software provided by the UPC and an economical investment would be needed for a more accurate study.

There is no intention of making any changes in the application or trying to improve it. Nevertheless, during the study some equipment placement and writing of codes have been done to make this evaluation. These scripts will be used whenever they are needed, especially when it comes to the synchronization between the three different capture systems. All the takes, information, tips, software materials and physical setups created can be used for future needs concerning the project of the application.

## 3. Literature review

### 3.1. State of the art

Traditionally, the validation of instruments for kinematic analysis has been performed by using a 3D optical motion capture system. However, the transfer of this method to clinical settings is limited due to its high cost, non-portable system, the space required and the complexity of the integration and analysis of the recorded images/data. It also needs a system calibration typically in the form of a recording session using specially dedicated accessories and reflective markers applied to the subjects. Analysis of parameters accuracy of optical motion capture require the use of up to ten cameras to reduce calculation errors [4].

The implementation of depth cameras provides a tool that simplifies the complexity of these studies. Nevertheless, validation of its accuracy is required. For instance, it has shown reliability in kinematic analysis of balance tests [5] compared to inertial sensors.

Comparing to 3D optical systems, less cameras are needed and, therefore, less space, lower cost, portability and the system is less invasive in human assessments. Depth cameras face challenges such as lighting conditions, occlusion and changes in subject's distance from the camera. These issues need to be addressed in order to obtain optimal accuracy. Some authors have developed methods to determine the accuracy of these cameras [6] in order to validate them for body images acquisition.

Depth cameras use two different technologies to obtain depth information:

- TOF (time-of-flight) measures distance by sending a pulse of light out from the camera and measuring the time it takes for the pulse to travel to an object and back.
- Active stereo technology works by triangulation, similar to multcameras systems that use trigonometry to calculate distances. In this case, the longer the baseline between image sensors, the more precise the measurement.

New technologies have been developed on these devices, like Light Detection and Ranging (LiDAR), which incorporate a scanner system resulting more accurate than TOF and stereo sensors, but at an increased cost.

Improvement on precision has been made in new models, as in Microsoft Kinect camera, whose second generation, has shown less average error.

Limitations of depth cameras might be lack of accuracy and robustness of the captured data in studies of human bodies, as they assume the subject is mostly in frontal pose, like in video gaming. This problem can be partially solved by adding multiple cameras [7], resulting in acceptable 3D images. Other issues are occlusion and range limitation as sensor measurements become more erratic. Again, an extra camera could enhance the results.

## **3.2. Fundamental notions**

### **3.2.1. Stroke**

Stroke is a disease that occurs when the brain stops receiving oxygen and nutrients because the blood vessel that carries them has been either blocked by a clot or bursted. When this occurs the brain cells that don't receive oxygen die and the parts of the body controlled by the affected area keep immobilized. It can affect the brain totally or partially and it is the nº5 cause of death in the USA. Strokes can be classified in ischemic stroke, caused by a clot, and hemorrhagic stroke, caused by a vessel rupturing, both preventing the blood from reaching the brain. The parts of the body that are controlled by the affected area of the brain will be motionless, causing paralysis and speech problems [8].

### **3.2.2. Rehabilitation**

Stroke rehabilitation is a program designed to relearn the skills lost after suffering from stroke, such as movement, speech, strength or daily living skills and therefore gain independence and quality of life. Many studies have demonstrated that people that participate in rehabilitation recover much better than those who don't.

It is centered around focused and repetitive actions. Those activities can be physical (motor-skill exercises, mobility training...), technology-assisted (robotic technology, virtual reality...), cognitive and emotional (therapy for cognitive and communication disorders, medication...) or other types of therapies that are still being investigated (noninvasive brain stimulation...).



It is recommended that rehabilitation starts as soon as possible (24 to 48 hours after the stroke) and it can last months or even years depending on the severity of the stroke. Many professionals play a role in this procedure, from specialists like doctors, rehabilitation nurses and physical therapists to speech and language pathologists, social workers or psychologists [9].

### **3.2.3. Telerehabilitation**

Telerehabilitation is a remote rehabilitation carried out by different technologies that provide evaluation, assessment, monitoring, prevention, intervention, supervision, education, consultation and coaching. Being able to rehabilitate from any place presents big advantages. It is an excellent way to ensure access to health care to economically privileged large cities but also to economically challenged environments [10].

Recent advances in telerehabilitation have led to the frequent use of it with patients that have suffered from a stroke. Innovative models of care including coaching, use of avatars to encourage recovery and transition support have put in doubt if in-person therapy has better results over it.

### **3.2.4. Activities of Daily Living (ADL)**

Activities of Daily Living (ADL) englobes the fundamental skills required to independently care for oneself. It is used as an indicator of a person's functional status, as its inability results in the dependence of other individuals or mechanical devices. In 2011, the United States National Health Interview Survey determined that 20.7% of adults aged 85 or older, 7% of those aged 75 to 84, and 3.4% of those aged 65 to 74 needed help with ADLs. They are divided into basic and instrumental ADLs [11]:

Basic ADLs:

- Ambulating
- Feeding
- Dressing
- Personal hygiene
- Continence
- Toileting

Instrumental ADLs:

- Transportation and shopping
- Managing finances
- Shopping and meal preparation
- Housecleaning and home maintenance
- Managing communication with others
- Managing medications

## 4. Depth Camera

A depth camera is a device that calculates the distance of objects from the camera. Together with a RGB camera, it can be used to detect objects in 3D, in this case the human body. It is the object of study.

### 4.1. Hardware

The depth camera used for this project is the *Real Sense D415* depth camera (Intel Corp., Santa Clara, SV, USA). It is a single device including two cameras: an infrared projector and a RGB sensor to capture the reflection of the beam of light (figure 4.1) [12].



Figure 4.1. Front (left) and back (right) image of the Real Sense D415 (Source: Intel)

The *D415* is connected to the computer where the data is saved via a USB cable. USB ports older than the USB port 3.0 version will not be detected by the camera. It is fabricated in Thailand or China, costs 272,00\$ in the official *Intel* website and offers shipping all around the world. Its technical specifications are showed in the table 1:

Table 4.1. Real Sense D415 Specs.

Parameter	Value
Use Environment	Indoor/Outdoor
Image Sensor Technology	Rolling Shutter
Ideal Range	0.5 m to 3 m
Depth Technology	Stereoscopic

Minimum Depth Distance (Min-Z) at Max Resolution	~45 cm
Depth Accuracy	<2% at 2 m
Depth Field of View (FOV)	65° x 40°
Depth Stream Output Resolution	Up to 1280 x 720
Depth Stream Output Frame Rate	Up to 90 fps
RGB Frame Resolution	1920 x 1080
RGB Frame Rate	30 fps
RGB Sensor Technology	Rolling Shutter
RGB Sensor FOV	69° x 42°
RGB Sensor Resolution	2 MP
Camera Module	Intel RealSense Module D415
Vision Processor Board	Intel RealSense Vision Processor D4
Form factor	Camera Peripheral
Camera Dimension (Length x Depth x Height)	99 mm x 20 mm x 23 mm
Connectors	USB-C* 3.1 Gen 1*
Mounting Mechanism	-One ¼-20 UNC thread mounting point -Two M3 thread mounting points

## 4.2. Software

The program used to capture the movements with the depth camera is an application created by professors and students from the EEBE that also contributed to this bigger project, called *Muvity* [13].

This application was created with the goal of providing post-stroke people the possibility to perform recovery from home in an interactive and more enjoyable way, being able to perform ADL with no issues (this version is still a trial beta and has not been commercially released). This application uses the *Nuitrack* libraries to establish its programming interface and the platform *Unity* to create the interactive avatars.



Figure 4.2. Nui track logo (Source Nui track)

Figure 4.2. Unity logo (Source Unity)

*Telerehab* is very easy to use once the necessary programs and libraries are installed. The interface is very intuitive and needs to be accessible to everyone as it is intended to be used for any subject from home. The application works by recognizing the different parts of the body and identifying the position of the joints. Note that the human skeleton is simplified and the number of degrees of freedom (DOFs) is lower than in the actual human body.

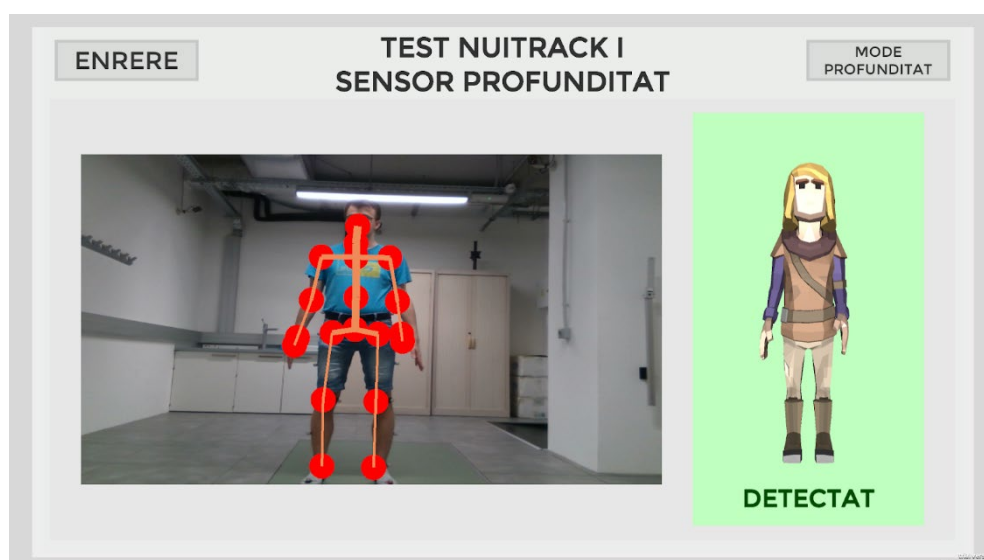


Figure 4.4. *Telerehab* application (Own source)

First, the user needs to log in. Physiotherapists or other specialists and patients will log into different modes and will have different options they can benefit from, so the first ones can have access to the information of the first ones and can follow their progres. See figure 4.5.

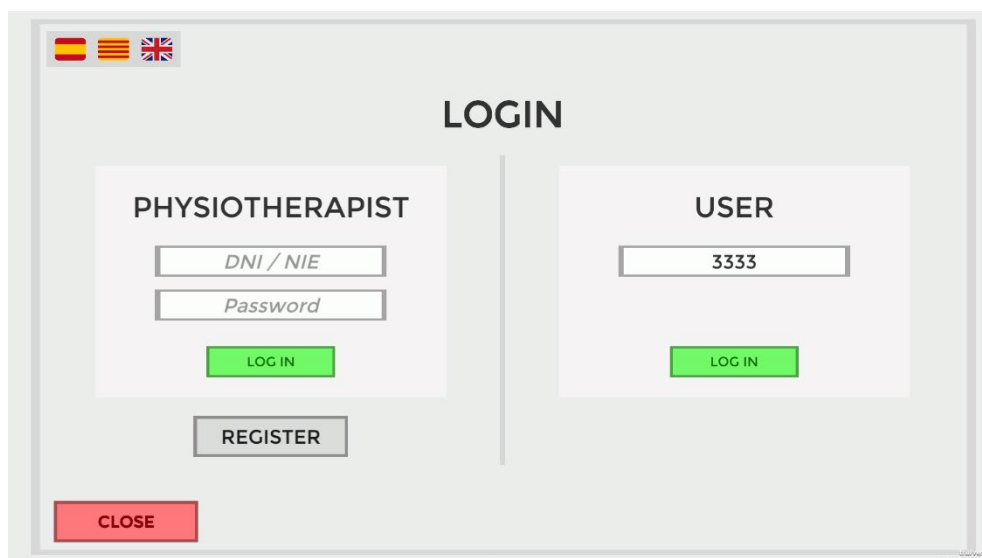


Figure 4.5. Telerehab log in (Own source)

Before starting the recording, it gives the user the option to run a configuration test of the depth camera (figure 4.6). Running a calibration is recommended to obtain more accurate data. The calibration ensures that the totality of the subject's body is in range with the camera.

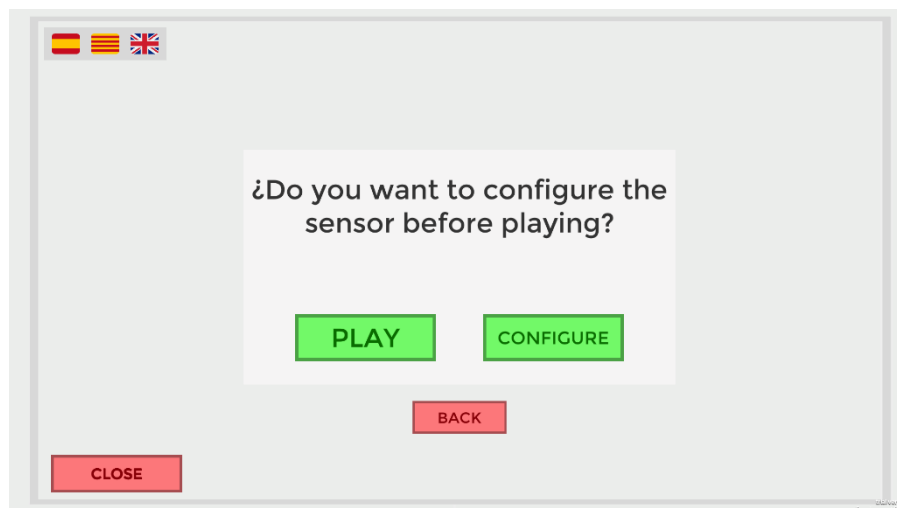


Figure 4.6. Telerehab configuration (Own source)

Once the configuration test is done the user can start doing the exercises proposed by the physiotherapist. The application offers the option of doing normal guided mobility exercises or to play some games that require more focus on the behalf of the patient and makes the exercises more entertaining. See figure 4.7.

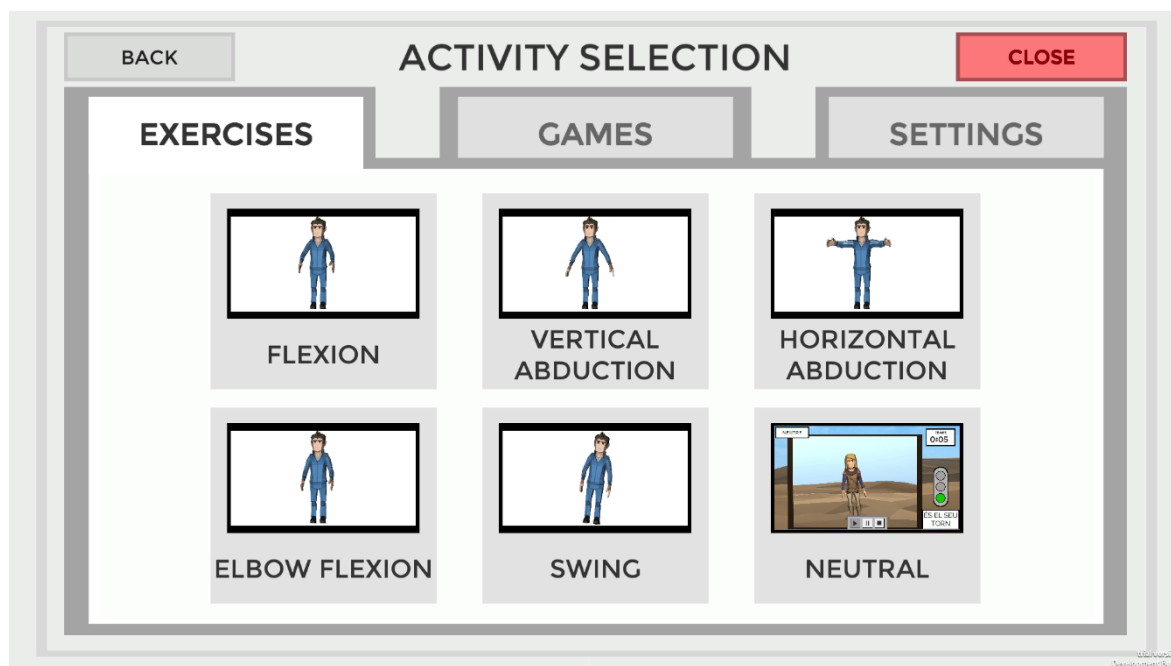


Figure 4.7. Telerehab menu (Own source)

One of the options besides the guided exercises and the games is the neutral recording mode, where the user is free to do and record the exercises he wants. This mode can be used for therapists and specialists so they can ask their patients to send the data of any exercises they would like them to do. This way, the range of different exercises the application can recognize is much wider. It is the mode used to record the exercises that were performed during this study.

In this neutral mode, an avatar appears on the screen following the movements of the user (figure 4.8). In this way, the patient can watch how he is performing the movement, make the corrections that are necessary and have more awareness of his body position. If the camera does not recognize any human body, the application will warn the patient and the avatar will stop following the patient's movements (figure 4.9). The data is saved in a frame-by-frame basis in a ".txt" file containing the position of the joints.



Figure 4.8. Telerehab neutral mode (Own source)



Figure 4.9. Telerehab neutral mode (subject not detected) (Own source)



## 5. Optical cameras

### 5.1. Hardware

The data captured with the depth camera is compared with the data obtained from an optical motion capture system that uses different optical cameras acting as receptors of the light reflected by special markers placed on specific positions of the body. These markers have reflective material on the surface so they can be easily identified and recorded by the optical cameras in a 3D space. It is very important that the room where the captures take place has the minimum natural light coming in to avoid noise to the system. Shiny objects in sight can also perturbate the take (the cameras can confuse them with markers) and cameras cannot move from the moment the calibration is done. The room where the captures took place during this study is the Biomedical Engineering Laboratory (BEL) of the EEBE (figures 5.1 and 5.2). This laboratory is completely isolated from natural light (it has no windows), the floors are made of special rubber and the cameras are fixed to the walls, so the result obtained is accurate and reliable [14].



Figure 5.1. BEL (Own source)



Figure 5.2. BEL (Own source)

The optical camera system used in this study incorporates *Optitrack Flex 13* (NaturalPoint Inc., Corvallis, PO, USA) motion cameras (figure 5.3). A total of six *Optitrack* cameras are allocated in the BEL, placed in a strategic and optimal way so they are all focusing in the middle of the room, which will be the place where the subjects will perform the different movements.

The system of optical cameras was set up at the laboratory in April 2022. Initial tests were performed in the SIMMA laboratory (EEBE, A8.40), with a system of six Flex 13 cameras. The initial tests consisted of analyzing and familiarizing with the optical system and making the optical camera position corrections necessary.

The *Optitrack Flex 13* optical camera has been chosen by EEBE for its qualities in terms of accuracy and fiability. Each *Optitrack Flex 13* camera costs \$1099 individually at the official website of the company and it is one of the most affordable cameras with these characteristics in the industry. Its specifications are the following [15]:

### Camera Body

- Width: 2.12 inches (53.8 mm)
- Height: 3.19 inches (81 mm)
- Depth: 1.67 inches (42.4 mm)
- Weight: 6.6 ounces (187 g)
- Mounting: 1/4"-20 tripod thread
- Status Indicators:
  - 2 digit numeric LEDs
  - 1 bicolor status LED



Figure 5.3. *Optitrack Flex 13* camera (Source: *Optitrack*)

### LED Ring

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

### Lens & Filter

- Stock Lens: 5.5 mm F#1.8
  - Horizontal FOV: 56°
  - Vertical FOV: 46°
- Optional Lens: 8 mm F#1.8
  - Horizontal FOV: 42°
  - Vertical FOV: 34°
- 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 : 6.144 mm × 4.9152 mm
- Pixel Size : 4.8 μm × 4.8 μm
- Imager Resolution : 1280 × 1024 (1.3 Megapixels)
- Frame Rate: 30-120 FPS (adjustable)
- Latency: 8.3 ms
- Shutter Type: Global
- Shutter Speed:
  - Default: 500 μs
  - Minimum: 20 μs
  - Maximum: 7.5 ms (at 120 FPS)

## Image Processing Types

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

## Input/Output & Power

- Data: USB 2.0
- Camera Sync: USB 2.0 (via OptiSync)
- Power: USB 2.0 @ 1 A

Flex 13 cameras must be connected to the PC via an OptiHub 2 in order for the LED Ring to be powered. Connecting the camera directly to the PC will result in the LEDs being disabled.

The *Optitrack Flex 13* system needs an extra device to synchronize the different cameras and to link them to a central computer that can save the data. This device is the *Optihub 2* (NaturalPoint Inc., Corvallis, PO, USA) and works as a master of the cameras (figure 5.4). An extra *Optihub* device was used to obtain a more optimal resolution (one *Optihub* device can handle up to five cameras) [16]. When the optical system has more than one *Optihub* device, one of them is defined as the master device and the rest as the slave device of the first one. It is very important to know which of them is the master device, as any synchronization with an external system will be done through this one. Each *Optihub* device costs \$329 individually at the official website. Specifications are shown below [17]:

### Size & Weight

- Width: 5.47 inches (138.9 mm)
- Height: 1.61 inches (40.9 mm)
- Depth: 3.64 inches (92.5 mm)
- Weight: 13 ounces (0.4 kg)
- Opto-isolated Input, (LV)TTL compatible
  - $V_i(\text{max})$  : 0.8V
  - $V_i(\text{min})$  : 2.5V
  - $V_o(\text{max})$  : 13V
  - Max Freq : 10kHz
- Divider: 1:1 – 1:15
- Trigger Modes
  - Rising-Edge
  - Falling-Edge
  - Either-Edge
  - High-Level Gated
  - Low-Level Gated
- Trigger Delay: 0 – 65ms
- Trigger Rate: 8 – 100 Hz

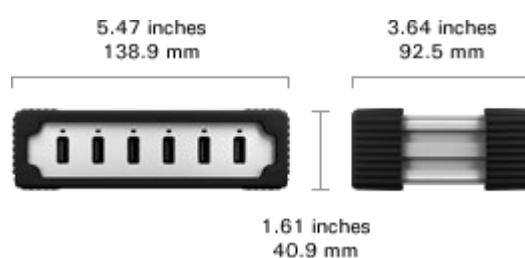


Figure 5.4. Optihub 2 (Source: Optitrack)

## 5.2. Software

The software used to run the optical motion capture system is *Motive* (figure 5.5) [18], a software designed to run and use the optical cameras in an easy and efficient way. Although the user's interface is friendly, it offers many options such as calibration, editing or labeling and it can be a bit difficult to familiarize with all the tools it has [19].

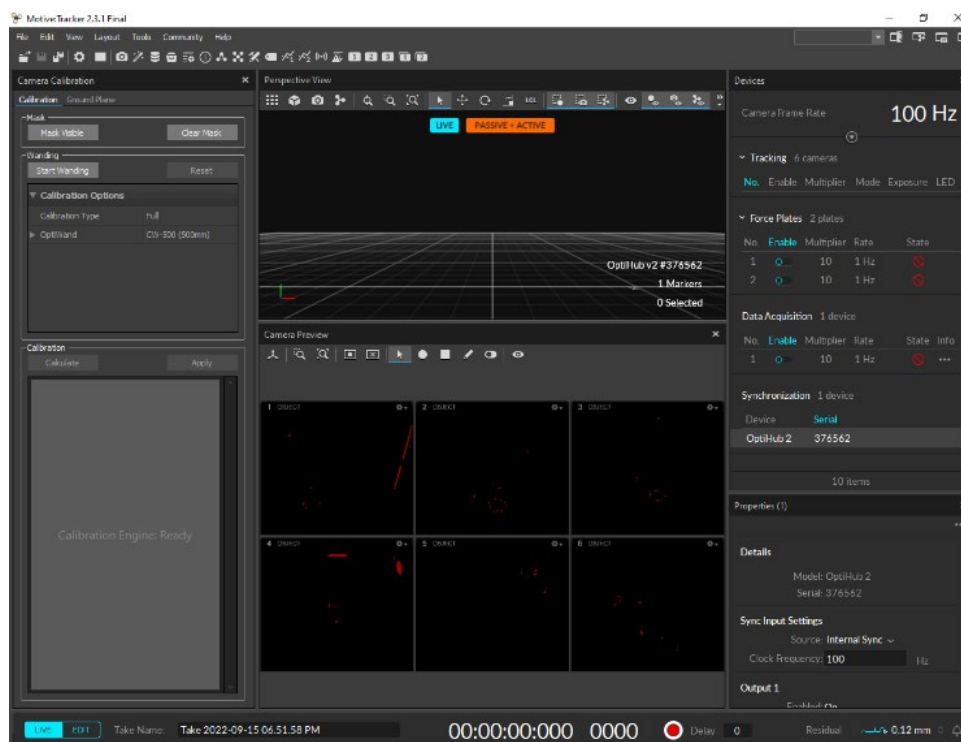


Figure 5.5. Motive interface (Own source)

### 5.2.1. Calibration

The first step before starting to record on *Motive* is to do the camera calibration. When the user launches the program, it will directly give him the option to calibrate the system. If a camera calibration has been performed earlier and the cameras or any object in the recording room have not been moved from its original position or orientation, this calibration can be used by choosing the option “Open a Camera Calibration”. See figure 5.6.

The Calibration process consists of:

- Applying masks on the objects that shine or zones where the cameras receive light that can disturb the recording.
- “Sweeping” or as technically speaking “wandering” all the room but especially the zone where the recording is going to take place. It is done with the *CW-500* wand (figure 5.7), a specific instrument with specific dimensions so that the application recognizes it. With these data

(trajectories of the wand markers), the software can calculate the relative position and orientation among cameras.

- Setting the ground with the CS-400 calibration square (figure 5.8), to fix the ground and the origin of the optical system. A coordinate system is defined within the point cloud.

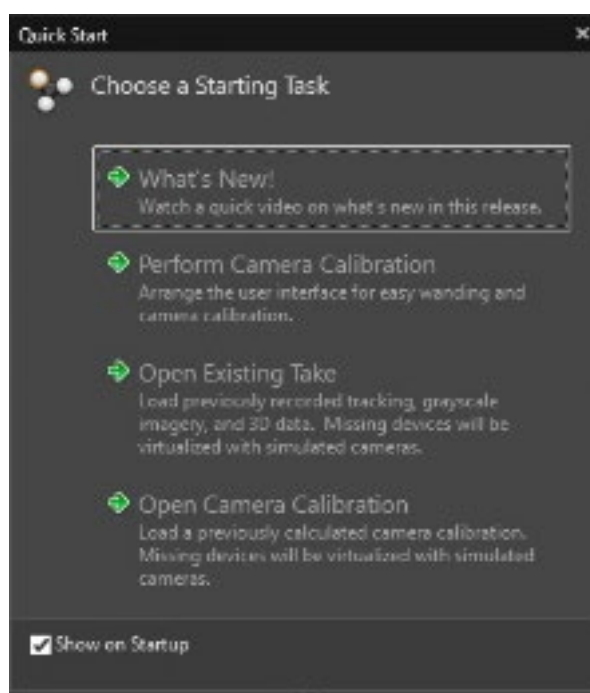


Figure 5.6. Calibration options (Own source)



Figure 5.7. Optitrack CW-500 wand (Source: Optitrack)



Figure 5.8. Optitrack CS-400 square (Source: Optitrack)

Calibration is the most important step of the process as a poor calibration can result in a poor take with a lot of noise and unsuccessful labeling of the markers. So, it is worth spending more time doing a good calibration, making sure there are as few objects in the room as possible and trying to move the fewer objects as possible after the calibration. The difference between the time and effort processing and working with a clear or noisy take is important.

Light parameters are an important factor to have in mind. They are the threshold values of exposure of the cameras, so even if the application has some default values, they can be changed according to the room characteristics and illumination.

During the calibration the user can see the zones where the wandering has been done and identify which zones have not been wanded yet, to obtain an optimal calibration (figures 5.9 and 5.10). The user can also see the number of samples recorded by each camera. The application has some threshold values to consider if the quality of the wandering is high or poor. Values below 10.000 samples is considered a poor value to calibrate. The camera frame rate is 100 Hz. Once the wandering is finished, the application calculates the relative position of the optical cameras and shows the result of it. See figure 5.11.

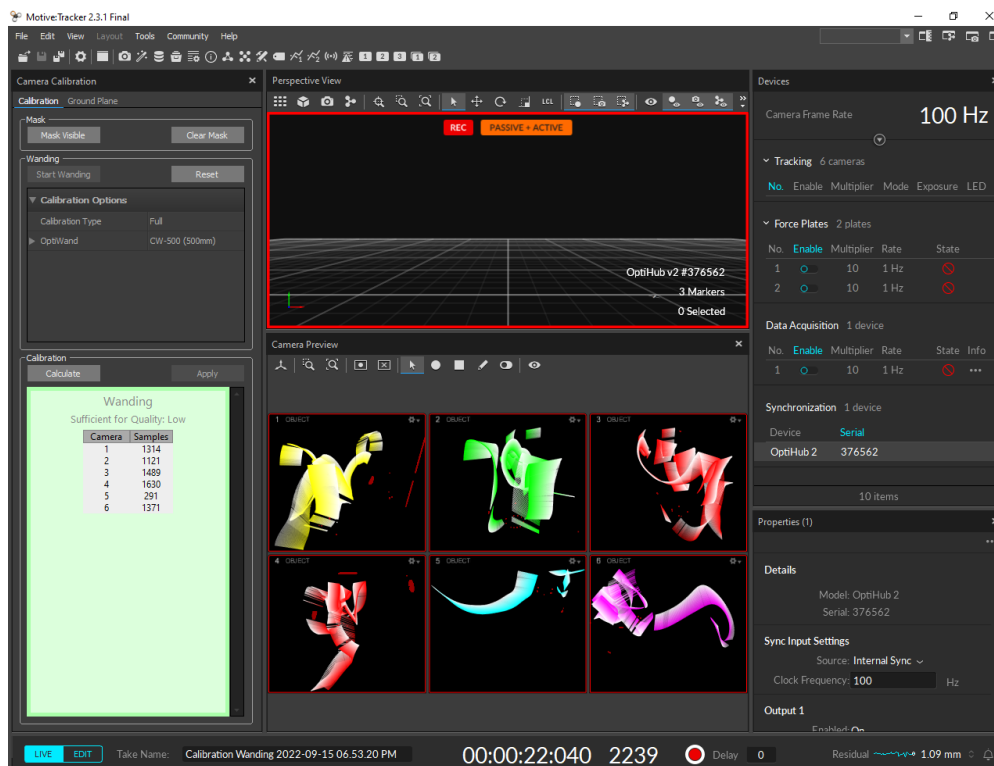


Figure 5.9. Beginning of the calibration (Own source)

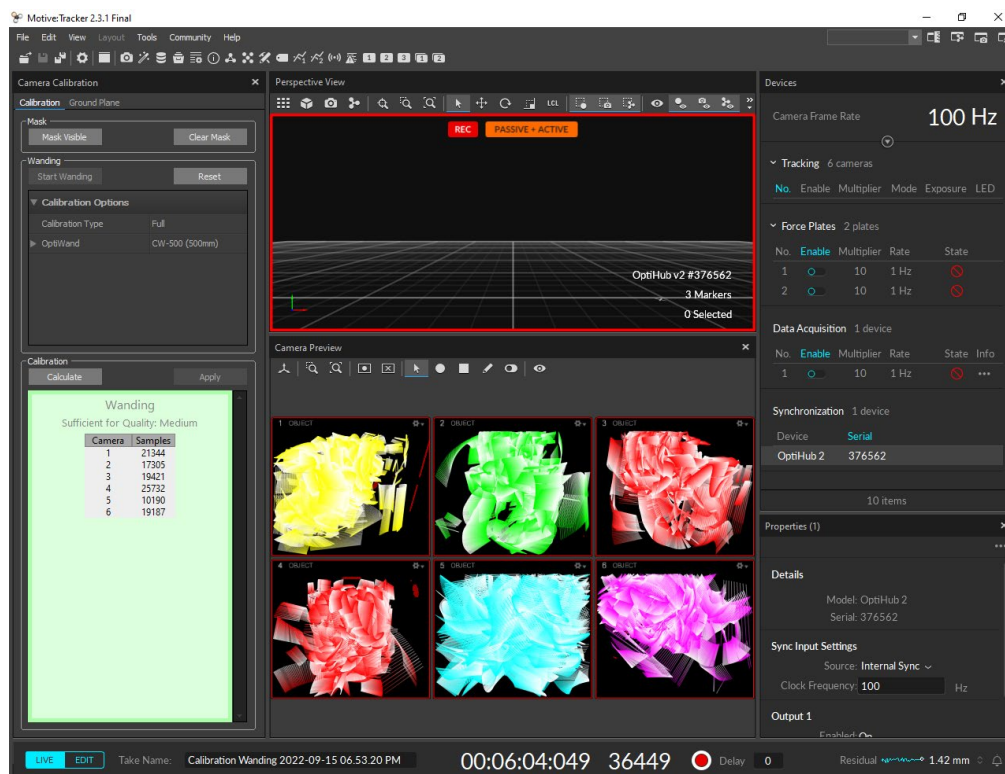


Figure 5.10. End of the calibration (Own source)

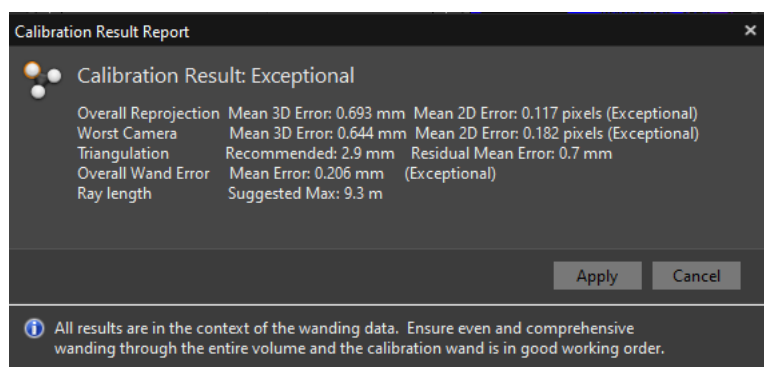


Figure 5.11. Calibration result (Own source)

Once the calibration is performed and accepted, this is saved and the system is ready to start the recording. If the cameras are fixed to a static place (figure 5.12), the calibration can be exported to be used in future sessions (figure 5.13). Nevertheless, the application has an option to recalibrate the cameras, starting from the older calibration but doing a quick wand in case the cameras have slightly changed their position. Furthermore, the continuous calibration option in the application, as its name suggests, is running a continuous calibration as the recording of the takes goes on.





Figure 5.12. Camera fixed on a static place (Own source)

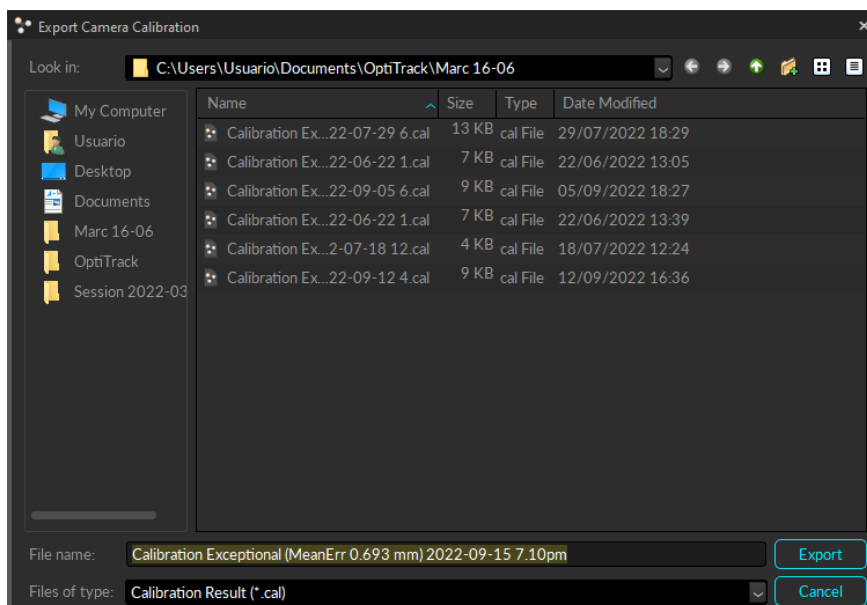


Figure 5.13. Calibration exportation (Own source)

### 5.2.2. Recording

The process of recording movements in *Motive* is very simple. The user only needs to click on the “record button” to start recording and click on it again to stop. The takes are saved all into the same session folder and the name assigned contains the session, date and time of the recording.

### 5.2.3. Labeling and editing

Once the takes are recorded, they need to be labeled for future analysis. The labeling process consists in assigning the corresponding names to each marker, defining and correcting errors or misunderstandings of the auto-label algorithm and filling the gaps in the frames where the marker has not been detected. The first step to start the labeling is to create an asset and to add all the markers that are expected to be found in all the takes (figure 5.14). Assets are a list with all the markers expected and they are used for labeling of reconstructed 3D markers in Motive. The assets can be copied into different takes, so there is enough creating the asset that is going to be used for all the takes one time and then exporting it (figure 5.15).

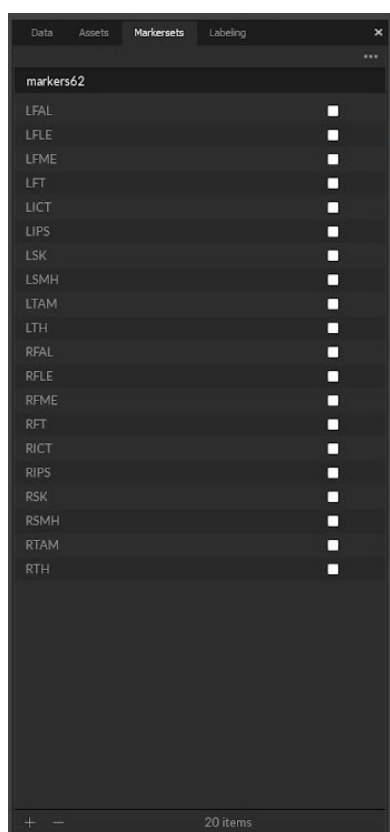


Figure 5.14. Asset marker's (Own source)

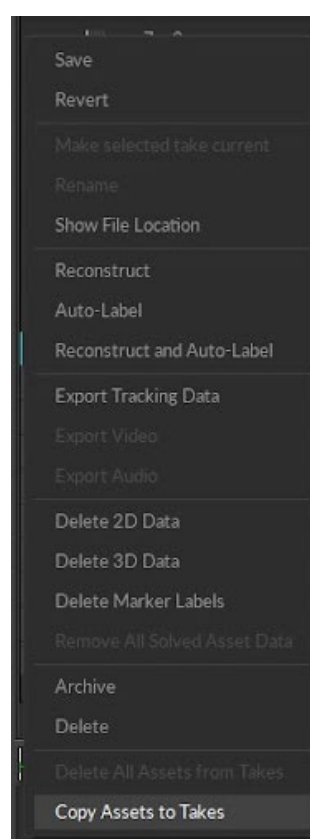


Figure 5.15. Copy asset to take (Own source)

When the asset is copied to the take, the actual labeling can begin. The process of labeling consists in trying to identify each marker that appears on the screen and assign its corresponding name. If the calibration is good, the auto-label will group the markers detected in the different frames as the same marker through all the frames. If the calibration is poor, the auto-label tool will not

recognize the markers through all the frames as one, and this will be a tedious task to be done by the user, going frame by frame trying to identify the markers. The markers that have not been labeled appear in orange, while the markers that have been labeled appear in white. See labeling pane on the left of figure 5.16 and real markers on the middle of figure 5.16. The default view is the perspective one, but the application offers the possibility to rotate the point of view or even change it to any isometric view when another point of view is needed to identify the markers. The false or unwanted markers can be left in the unlabeled markers pane or else be removed (figure 5.17).

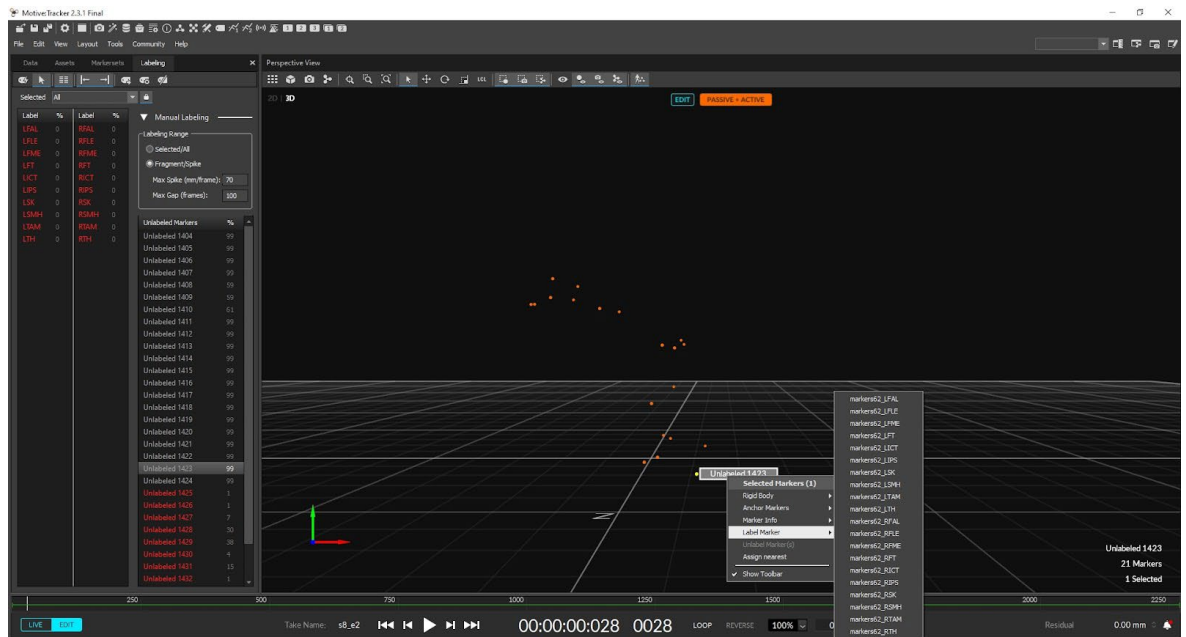


Figure 5.16. Labeling (Own source)

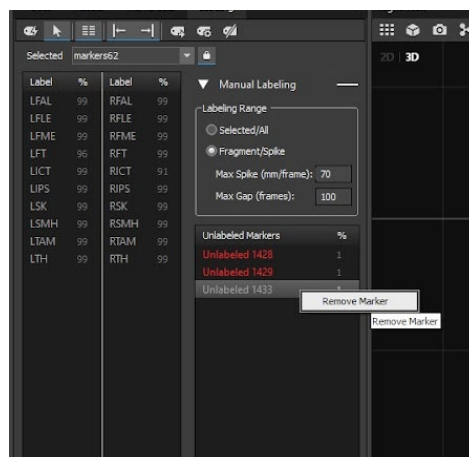


Figure 5.17. Removing markers (Own source)

The markers pane shows the percentage of reconstructed trajectory of each marker. Markers with values above 95% are considered acceptable, while markers with values below 80% have to be used and analyzed with caution as their reliability is low. Finally, labeled takes can be polished with the editing tool and the help of the graphic pane when the values of incidence of the markers are not 100%. Some programs that are used to visualize the takes assign the value (0,0,0) when there is no information on a marker, so it can be convenient to fill these gaps. The editing tool offers different options to improve the quality of the takes such as smoothing the take by removing the vibrations of the markers with a low-pass filter or filling the gaps where the cameras have not detected a specific marker. Different methods can be applied to fill the gaps. These methods are constant, linear, cubic, pattern-based or model-based. The method to be used depends on the percentage of incidence and if there are some markers with similar movements expected during the range to be filled. The cubic method uses a three degrees polynomial interpolation and it is a good option when markers appear in a high percentage of time frames while the pattern-based method is the better option for markers with a low percentage of apparition and with a constant relative position to another marker. See figures 5.19 and 5.20.

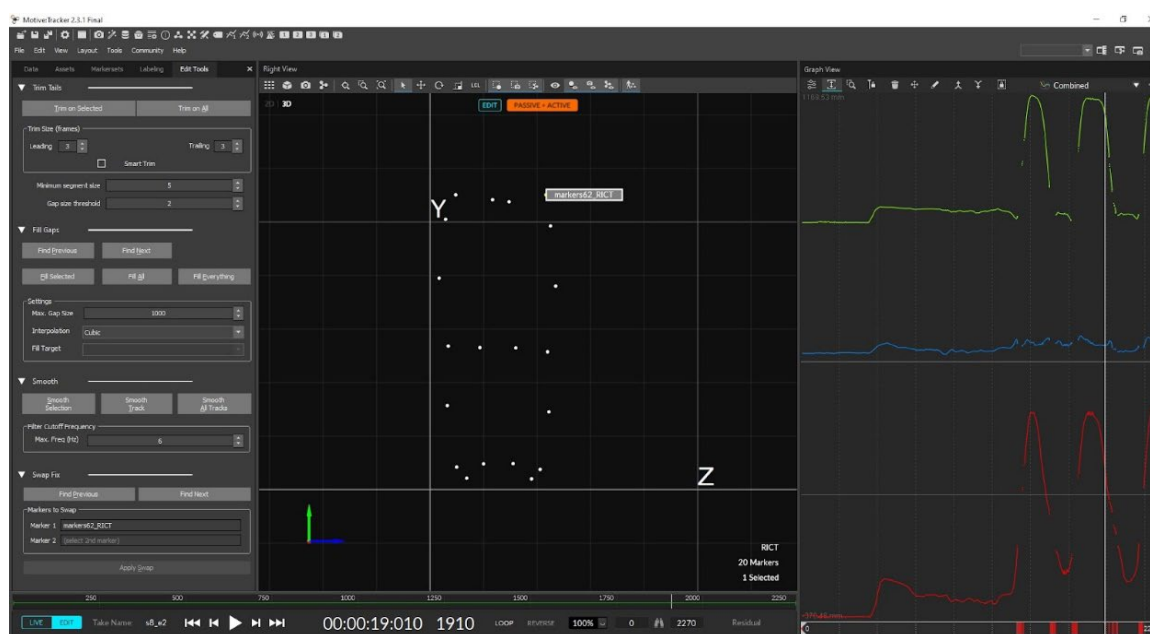


Figure 5.19. Take before filling the gaps (Own source)

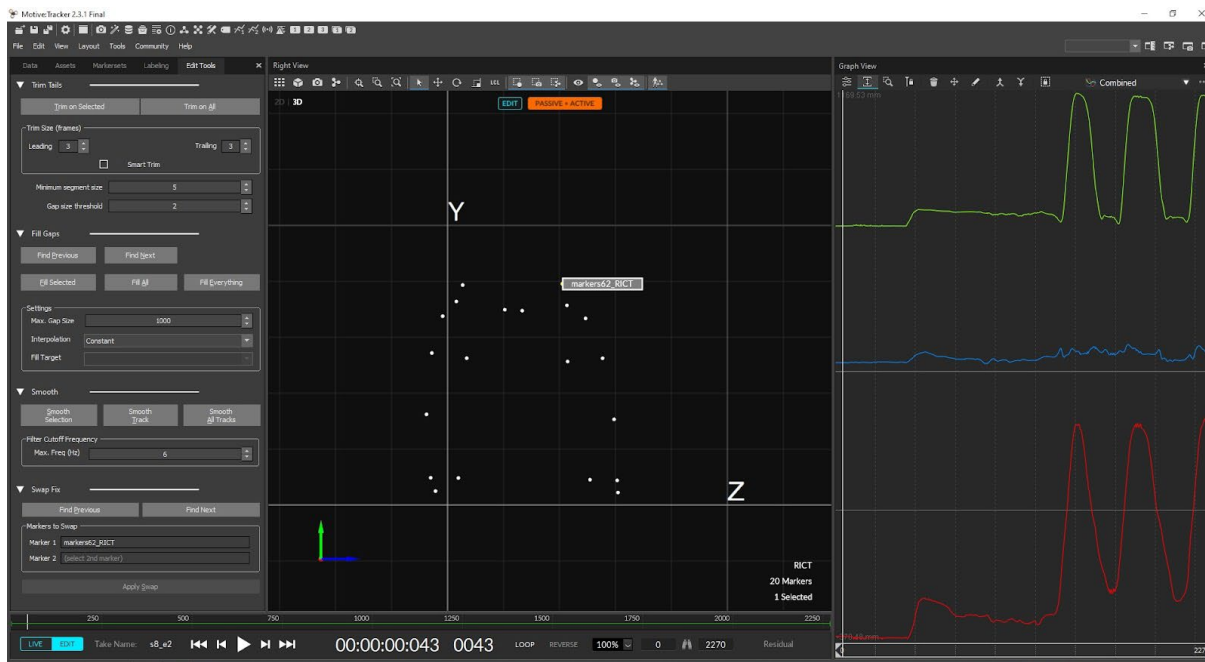


Figure 5.20. Take after filling the gaps (Own source)

## 6. Force plates

### 6.1. Hardware

The force plate used to capture the ground reaction forces (GRF) is the *Accugait-Optimized* (ACG-O) (AMTI, Watertown, MA, USA). In the BEL there are two AMTI plates and they are fixed on the ground. The two force plates have a separation of 8 cm and the second plate has a deviation of 30 cm to the left (Figure 6.1). The technical specifications of the device are the following [20]:

General specifications:

- **Dimensions:** 502 x 502 x 45 mm
- **Weight:** 11.4 kg
- **Temperature Range:** -18°C to 50°C
- **Channels:** Fx, Fy, Fz, Mx, My, Mz
- **Mounting Hardware:** Not Required
- **Sensing Elements:** Hall Effect
- **Amplifier:** Built-In
- **Outputs:** Digital (USB 2.0)

Capacities:

- **Fx.Fy Capacity (N):** 445
- **Fz Capacity (N):** 1334
- **Mx Capacity (N/m):** 226
- **My Capacity (N/m):** 226
- **Mz Capacity (N/m):** 85



Figure 6.1. Force plates (Own source)

## 6.2. Software

AMTI offers a clean and simple package for the data recording, saving and editing, but the interface used to do so in this study is a *Matlab* script (MathWorks, Inc., Natick, MA, USA) using the *C++ AMTI API*.

## 7. Methodology

### 7.1. Motion captures

For this study a total of ten subjects were recorded in the BEL, performing ten different exercises of ADL per subject. The subjects were healthy men and women between 21 and 56 years old, 51 kg and 80 kg of weight and 1,65 m and 1,99 m tall. Unfortunately, the first takes turned out to be unusable for the comparison as changes were done in the methodology during the process. These takes served as trial tests and were used to make the appropriate corrections. Some of these corrections consisted in doing a better calibration, adjusting the camera placement or covering shiny objects. Finally, the comparison is based on the subject whose takes had the best quality for the study. This subject is the subject nº8 and is a 25 year old man, 1,99m of height and weighing 80 Kg.

The position of the markers was chosen according to the *C-Motion Wiki* documentation [21]. The markers were placed in body landmarks like joints or the tip of a bone, but also in between these when there is a long distance between them. A symmetric distribution is followed, so there were the same markers on both sides of the body. It was very important that the markers were placed either directly over the skin or on skinny clothes so that the marker did not move relatively to the body.

The names of the markers and their placement is showed in the following list and figures 7.1, 7.2, 7.3, 7.4 and 7.5 (RTH and LTH are placed at the middle of the thighs and RSK and LSK at the middle of the tibias):

- RICT/LICT
- RIPS/LIPS
- RFT/LFT
- RTH/LTH
- RFLE/LFLE
- RFME/LFME
- RSK/LSK
- RFAL/LFAL
- RTAM/LTAM



- RSMH/LSMH



Figure 7.1. Pelvis markers (Source: C-Motion Wiki)

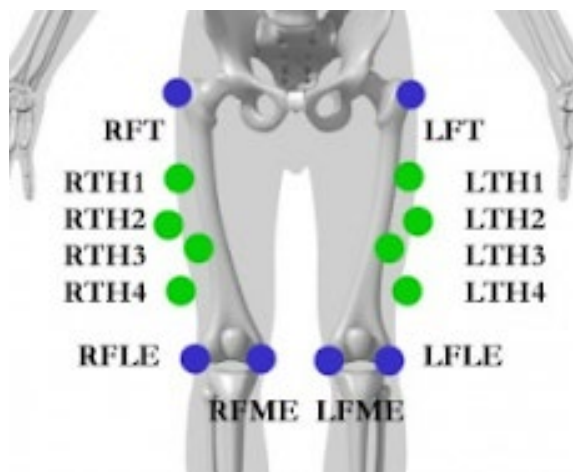


Figure 7.2. Thigh markers (Source: C-Motion Wiki)

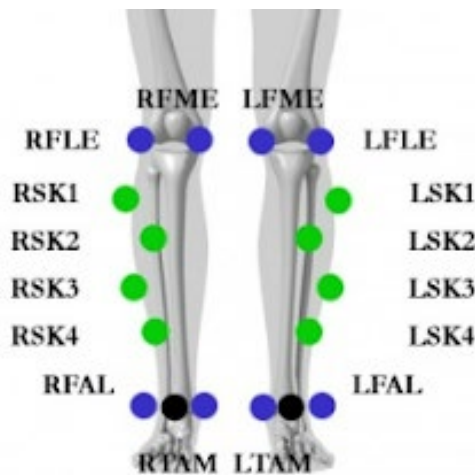


Figure 7.3. Tibia markers (Source: C-Motion Wiki)



Figure 7.4. Foot marker (Source: C-Motion Wiki)



Figure 7.5. Markers on subject (Own source)

### 7.1.1. Movements

At the beginning of each take, the subject had to lift and lower the left foot three times. This served to do the synchronization between the depth camera and the optical camera system later. The actual exercises performed by the participants and used to do the comparison were movements simulating ADLs like walking, standing up or step up [22] [23] and are the listed in the table 7.1 (figures 7.6 to 7.15 illustrate the movements):

Table 7.1. ADL exercises (Own source)

Nº	Movement	Description	Sequence
1	Walking	Normal walking over the plates	Three steps forward, first the left foot on the first plate, second the right foot on the second plate and finally the left foot outside both plates.
2	Standing up	Standing up starting from a sitting position on the chair and sitting again	Starting from a sitting position and standing up/sitting three times. The chair is not on top of any plate but both feet are.
3	Seating quadriceps	Sitting from a chair, doing a contraction of the quadriceps to lift foot	Starting from a sitting position and lifting each foot twice, alternating sides. The chair is not on top of any plate but both feet are.
4	Leg abduction	Lateral abduction of the leg	On the top of a plate, two repetitions each side, alternating sides.
5	Squats	Normal squats exercise	On top of a plate, three repetitions.
6	Skipping	Slow skipping, taking knees up, without jumping	On top of a plate, two repetitions per leg, alternating sides
7	Hip external rotation	Hip external direction	On top of a plate, two consecutive repetitions per leg.
8	Hip internal rotation	Hip internal rotation	On top of a plate, two consecutive repetitions per leg.
9	Side swinging	Swinging left and right	On top of a plate, swinging from left to right two times.
10	Frontal swinging	Swinging forwards and backwards	Swinging forwards and backwards two times, left foot on the first plate and right foot on the second one.



**Figure 7.6.** Exercise 1: Walking (Own source)



**Figure 7.7.** Exercise 2: Standing Up (Own source)



**Figure 7.8.** Exercise 3: Quadriceps on a chair (Own source)



**Figure 7.9.** Exercise 4: Leg abduction (Own source)



Figure 7.10. Exercise 5: Squats (Own source)



Figure 7.11. Exercise 6: Skipping (Own source)



Figure 7.12. Exercise 7: Abductor external rotation (Own source)



Figure 7.13. Exercise 8: Abductor internal rotation (Own source)



Figure 7.14. Exercise 9: Lateral swing (Own source)



Figure 7.15. Exercise 10: Frontal swing (Own source)

### 7.1.2. Setup

The camera was placed on top of a stool with the purpose to have the camera at the same height as the subject's hip (figure 7.16) to record in a direct angle and avoid having any perspective that can affect its accuracy, and at a distance of approximately three meters from the force plate (the origin of the system). See figures 7.17 and 7.18 to see distribution of the recording setup.



Figure 7.16. Depth camera colocation (Own source)



Figure 7.17. Distribution of the BEL (Own source)



Figure 7.18. Distribution of the BEL (Own source)

### 7.1.3. Synchronization

The synchronization, both temporal and spatial, of the three recording systems was one of the main and more important tasks of this study.

The first step of the synchronization was to assign the point (0,0,0) at the left-bottom corner of the first force plate. This was done during the calibration of the optical cameras system by placing the *CS-400* calibration square at the edge of the force plate. To do the time synchronization of the optical cameras system with the force plates a *Matlab* code developed by *AMTI* to record takes with the force plates was modified to trigger and stop the recording of both of the systems. See figure 19 to see the *Matlab* visual interface. An *Arduino Uno Rev3* board (Arduino, Monza, IT) was used as an intermediate between *Matlab* (the computer) and the *Optihub* device. It was used to create the voltaje difference to trigger the optical cameras system recording when it was activated in the *Matlab* code. As mentioned, when it comes to the synchronization between multiple devices, the *Optihub* device can act as master or as a slave. If it acts as a slave, like it was in the case of this study, it needed to be in “Sync In mode” and the synchronization parameters had to be assigned in

*Motive.* In this study the *Optihub* was configured so that it is expecting a “High Gated” signal for it to be triggered (figure 7.20). The recording button needed to be clicked before and after each take, but the time frame it started and stopped the recording was determined by the external master device. If the *Optihub* did not receive any signal the recording did not take place. The time synchronization of the depth camera with the optical cameras system (and therefore also with the force plates) was performed via a *Matlab* code that detects the minimum value of the foot height during the recording of the synchronization movements in both cameras and calculates the delay between them. This delay was added to the take in question.

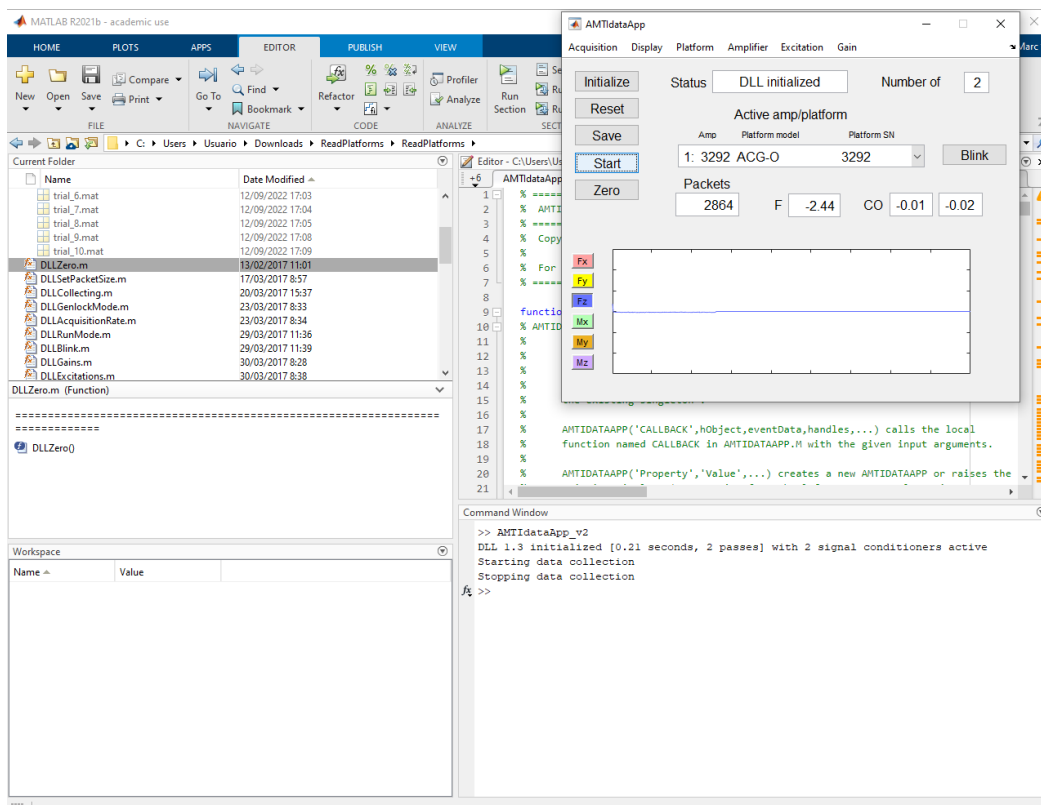


Figure 7.19. AMTI interface created with Matlab (Own source)



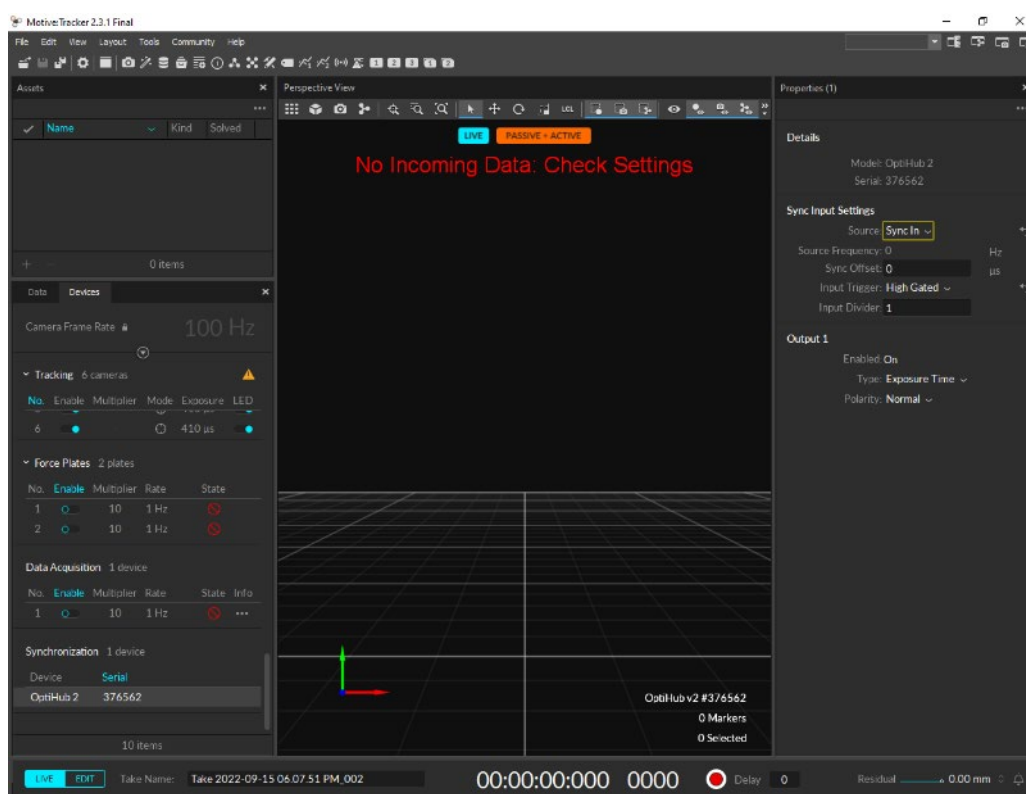


Figure 7.20. Motive external synchronization (Own source)

## 7.2. Processing the data

The tracking data exported from *Motive* was a “.csv” file while the data saved from the depth camera was a “.txt” file. These files could be converted into a “.trc” file using *Matlab*. These “.trc” files were opened and visualized with *OpenSim* (NCSRR, Stanford, CA, USA) with the “Preview experimental data” option (figure 7.21). *OpenSim* is a biomechanics software for modeling and simulation of movement. This software was used to convert the data containing the positions in the space of the markers into biomechanical moments. To do so, a human skeleton model was modeled to the real dimensions and weight of each subject using the data obtained during the captures. This was done by scaling a generic model (Figure 7.22), placing the markers recorded with both motion captures systems on the model (figure 7.23), assigning the weight of the subject (figure 7.24), the lengths of the parts of the body to scale (figure 7.25) and the weight each marker would have in the scaling (figure 7.26). The weights that the markers were assigned depended on the accuracy of its placement. Afterwards, the movements

recorded were performed by the scaled model (figure 7.27). To achieve this step the inverse kinematics tool of *OpenSim* was used and the joint angles were saved in a “.mot” file. Meanwhile, the force plates data saved in a “.mat” file was also converted into a “.mot” file using Matlab.



*Figure 7.21. Experimental data visualised in OpenSim (Own source)*



*Figure 7.22. Generic model (Own source)*



Figure 7.23. Generic model with markers from asset (Own source)

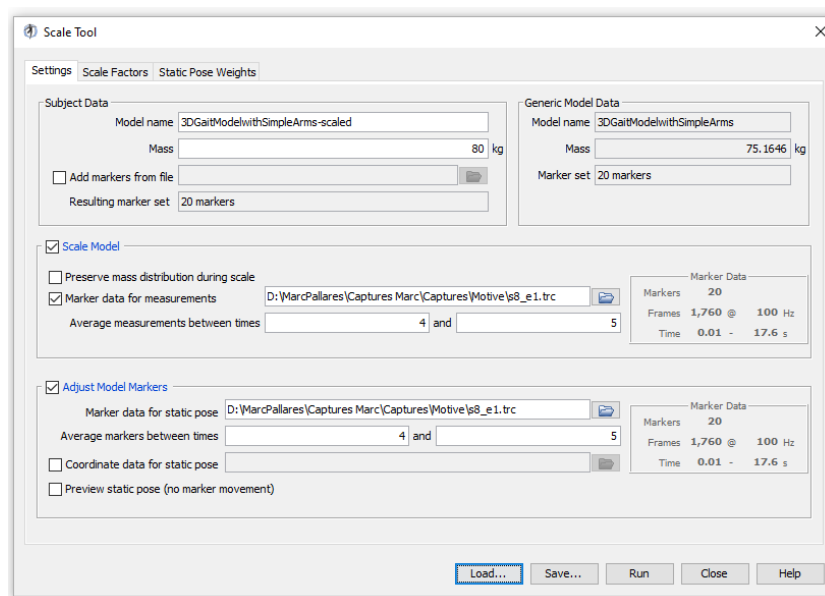


Figure 7.24. Scaling (Own source)

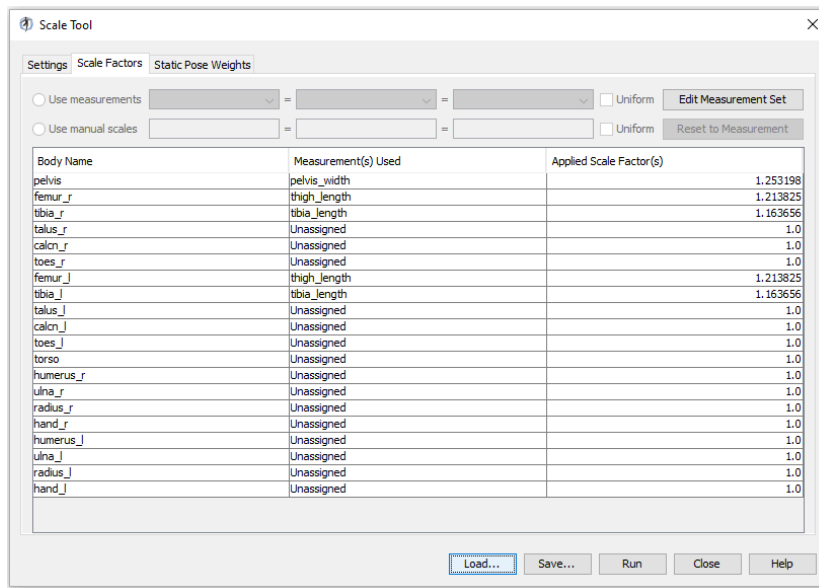


Figure 7.25 Scaling body lengths (Own source)

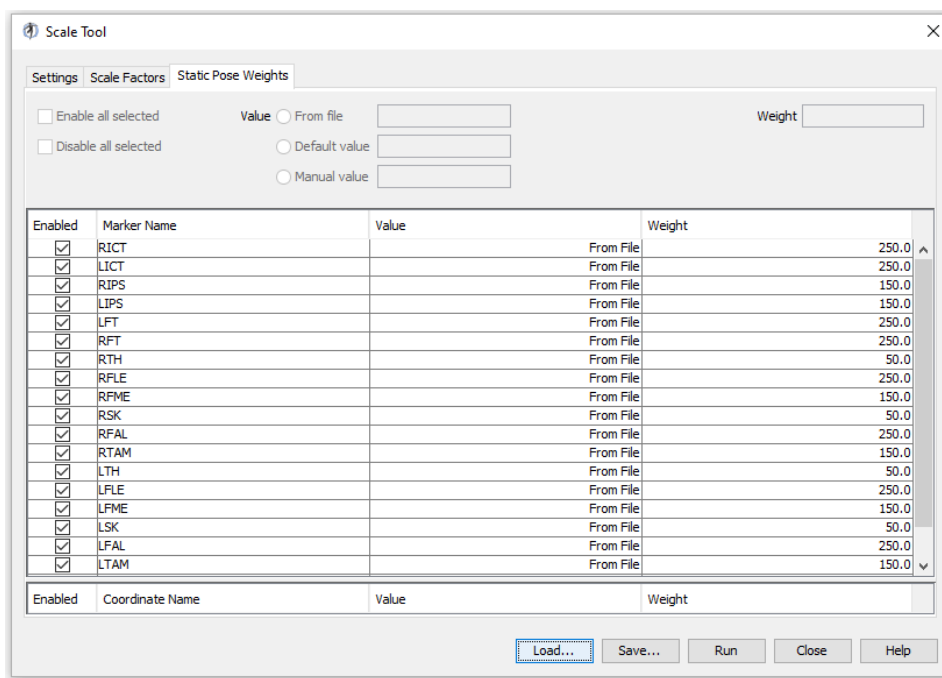


Figure 7.26. Scaling marker weights (Own source)



Figure 7.27. Scaled model (Own source)

### 7.3. Comparison of the data

The comparison between both motion capture systems was based on the difference on joint angles. The joints that have been evaluated are the hips and the knees, as they are the more important joints which have been recorded with the two motion capture systems. The joint angles were obtained by doing an inverse kinematics analysis with the Inverse Kinematics tool of *OpenSim*. The program runs the inverse kinematics on the scaled model tracking the movement recorded. The plotting was performed in *Matlab*.

## 8. Results

### 8.1. Synchronization

The synchronization between the optical cameras and the force plates was performed without losing time frames, as shown in figure 8.1. Synchronization has been one of the main issues of this study, and the accuracy of it has led to the opportunity to do a deeper and reliable thesis. The results in this section are more than satisfactory.

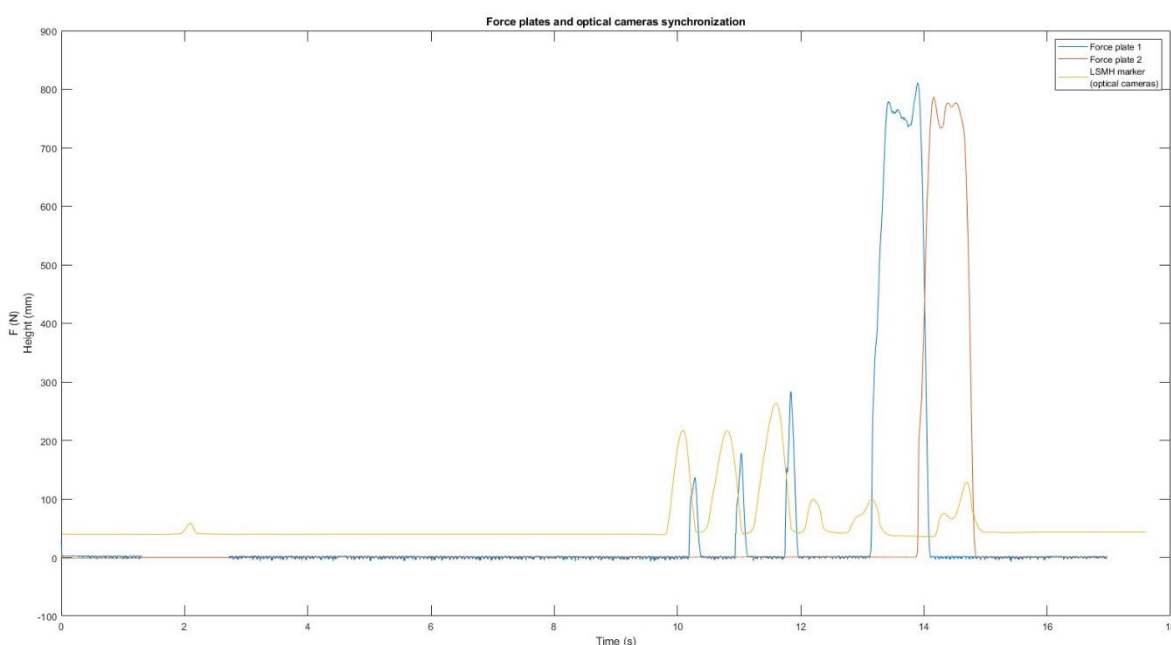


Figure 8.1. Synchronization between optical cameras and force plates (Own source)

### 8.2. Comparison

The results obtained during the comparison study are plotted in different graphics and the correlation coefficient of both methods is calculated. On one hand, graphics show good results in general. The flexion-extension angles at the hip and knee are the angles captured with the depth camera with higher accuracy. In figure 8.2, consisting of the leg abduction exercise, the two motion capture systems have obtained trajectories nearly identical. The depth camera does present more vibrations in its takes, specially when the movement analysed is a rotation or a part of the body that is more or less stable

(figure 8.3). In these cases, the captures obtained with the depth camera are relatively more distanced from the optical cameras takes. If magnitude is the parameter taking into account, the depth camera can be considered an accurate recording system. There are some exceptions though. Occasionally, the depth camera loses the human body reference completely and then the results obtained are considered nul. This happens specially in the “standing up from the chair” and “quadriceps from the chair” (figure 8.4 and 8.5), where the depth camera partially loses sight of some parts of the subject body like the thigh. Figure 8.6 shows an example of a take where the depth camera stopped recording suddenly. The graphics with all the results are included in the appendix of this report, while an example of the most significant results are synthetized in this section.

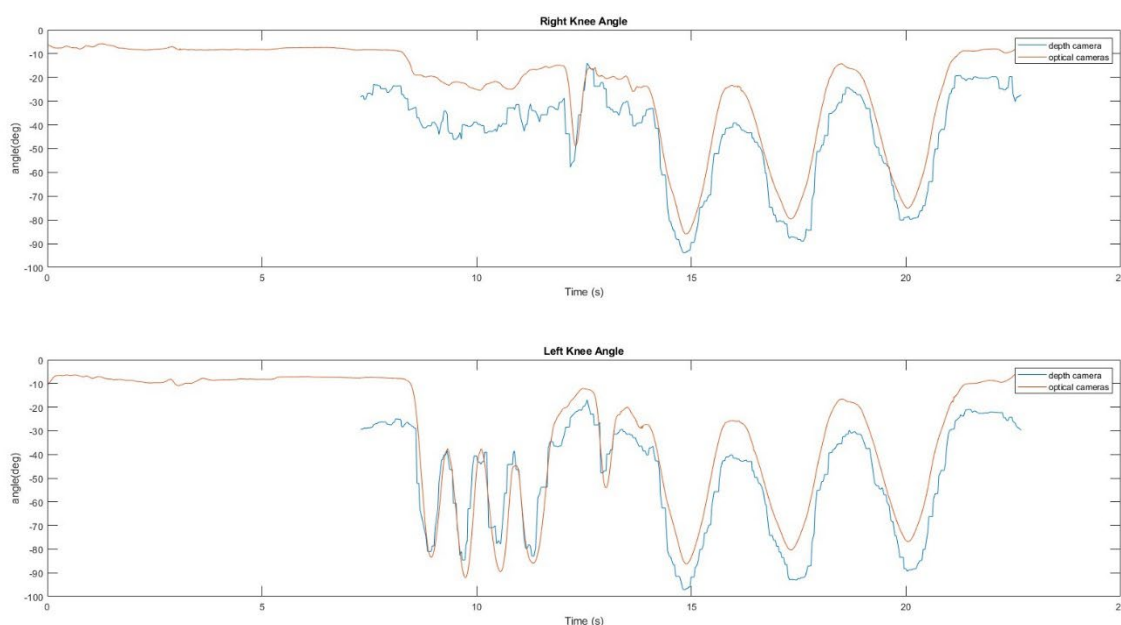


Figure 8.2. Joint angles of the knee during leg abduction exercise (Own source)

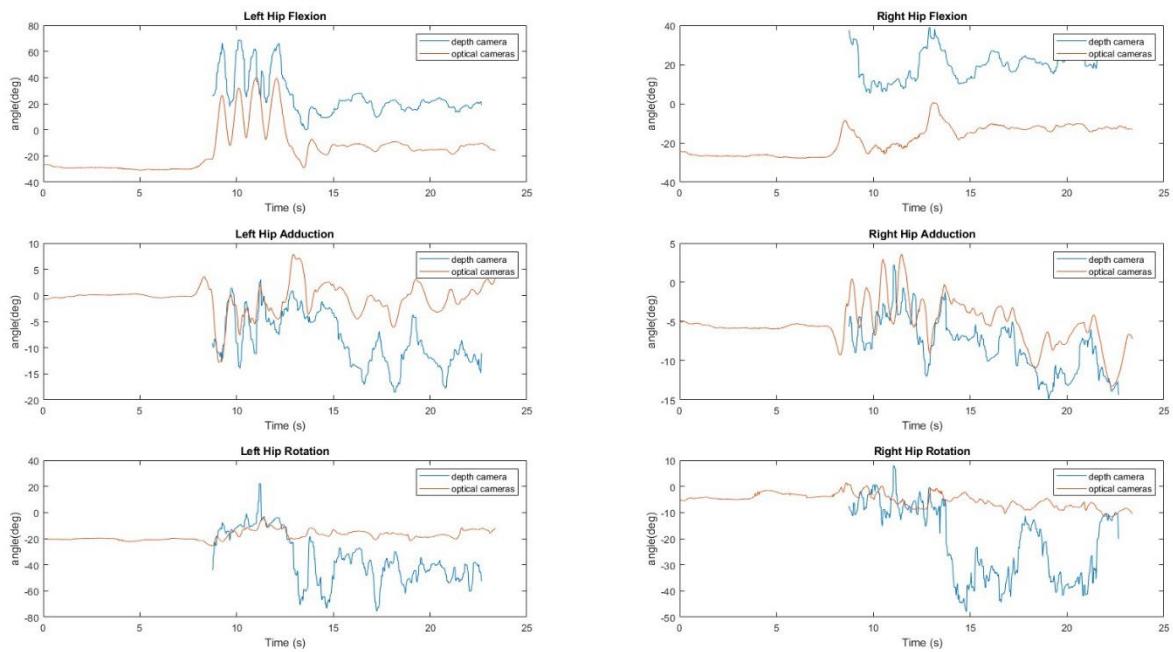


Figure 8.3. Hips angles during lateral swing exercise (Own source)

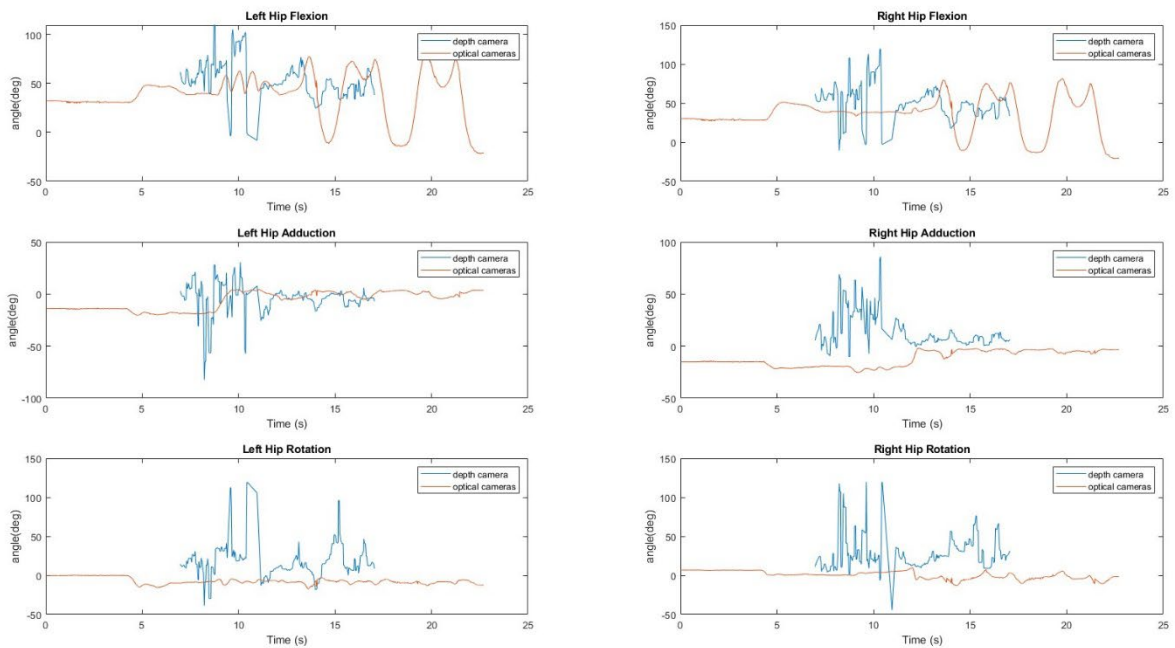


Figure 8.4. Hips angles during quadriceps from the chair exercise (Own source)



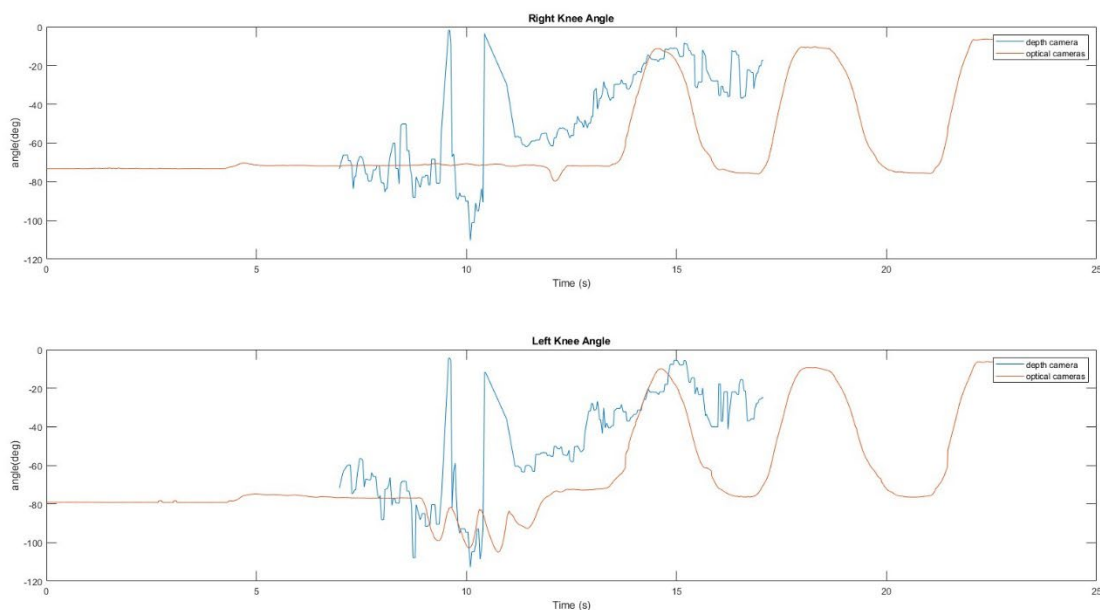


Figure 8.5. Joint angles of the knee during quadriceps from the chair exercise (Own source)

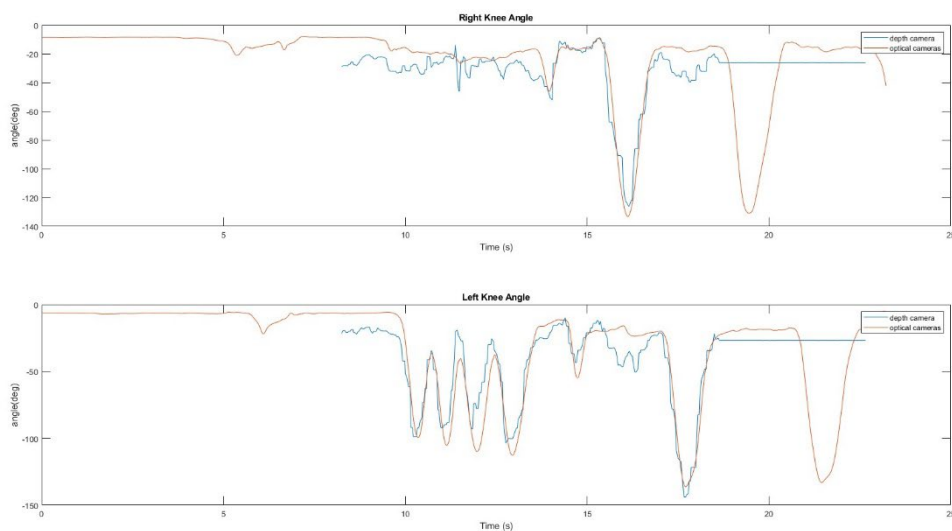


Figure 8.6. Joint angles of the knee during skipping exercise (Own source)

The correlation coefficient has also been calculated to have a quantified result. Takes where the recording was considered null (exercices nº2, nº3 and nº6) are not considered in the result of this parameter as it is an experimental error and it would varie considerably the result. The table below shows the average values of the correlation coefficient depending on the joint evaluated:

Table 8.1:

Joint evaluated	Correlation coefficient value
Hip flexion	0,84
Hip adduction	0,69
Hip rotation	0,21
Knee flexion	0,82

This values agree with the results obtained from the plots: joint flexion can be evaluated with a high accuracy while joint rotation is not a reliable value. The results obtained in each take are displayed in the appendix of this report.

## 9. Environmental Impact Analysis

The work in this study had no direct environmental impact derived as it was a comparison study, but the creation and use of *Muvity* does, so the environmental impact analysis will focus on the indirect effect that it has.

On the one hand, *Muvity* has a positive impact on the environment. The fact that patients can stay at home to do their rehabilitation and do not need to take any transport means a huge reduction in fuel or other power sources used to go to the medical center, and therefore a reduction in CO2 emissions. The calculation of the quantity of CO2 emissions is an approximation and it is based on a worst case scenario, where all the patients take the car to move. Averages values of distance from the medical center, CO2 emitted per kilometer and number of stroke patients in the United States have been used for the calculation [24] [25]. See results in table 9.1 and equation 9.1.

Parameter	Value (in ISO metrics)
Distance between patients and medical centers	5 km / visit
Gas emission	251,03 gCO2 / Km
Anual stroke patients	795.000 patients / year
Anual visits	50 visits / patient

Table 9.1. Average values of distance, gas emission, stroke patient, and visits (Own source)

$$CO2 \frac{g}{year} = 5 \frac{Km}{visit} \times 251,03 \frac{gCO2}{Km} \times 795.000 \frac{patients}{year} \times \frac{50 visits}{patient} = 49.892.212.500 \frac{gCO2}{year}$$

**(Eq. 9.1)**

According to this optimistic approximation, *Muvity* (added to other applications of telerehabilitation) could reach a positive impact on the environment by reducing 49.892,2 tones of CO2 grams per year only in the United States.

On the other hand, the fabrication and residual cost of the fabrication of the depth camera has a negative impact on the environment. This device is made of different toxic materials such as Cadmium, Mercury or PNC's, that difficults the task of recycling the device. In the EU, the device is considered a Waste Electrical and Electronic Equipment. This means the product must not be disposed of with household waste [26]. This negative impact should be deeply analyzed to quantify the long-term effect on the environment.

## 10. Conclusions

The fact that telerehabilitation is the future of rehabilitation of chronic disease is a common opinion nowadays, and for sure it presents a lot of advantages. However, the accurate motion systems still have high prices and are not accessible to everyone, while more accessible devices like depth cameras have to be used with caution. At the same time the range of movements the depth camera can capture without losing the joints position is limited by movements where the body is completely frontal and the position of the body does not vary much from a standing standard position.

In conclusion, depth cameras are a reliable tool in human kinetic studies, though they are still not reaching the accuracy and precision of state-of-the-art optical systems. Nevertheless, advantages described above and future development of device technologies, should set these cameras as a standard tool, and needs to be introduced progressively and can be used for the moment for rehabilitations treatments that present low risks.

The fact that the comparison between both methods is based on only the takes recorded in one subject makes the study reasonably aleatory and comparison with more subjects is necessary to draw clear conclusions.

This project is part of a bigger project and with more time and economical resources better results can be obtained and a more accurate and reliable study can be done. The definition or creation of an algorithm that can realise the process of analysis is a interesting option to optimise all the procedure and therefore be able to compare more data. Although not having arrived to the established goal of comparing both motion capture systems at a joint dynamics and power level at the beginning of the study, it has contributed with the project in other ways even if the results are not very clear and reliable. The setup of the BEL, writing different *Matlab* codes (specially for the synchronization) and achieving new milestones are some examples. However, the data is ready to be analysed and it is the next step to measure and test the depth camera accuracy at a deeper and more reliable level. Recorded takes and data, besides the knowledge and breakthroughs done during this study can be used in the future of this project to obtain better results that can give a clearer opinion on the depth camera state.

## 11. Budget and Economical Analysis

The economical analysis of this study is divided in three main groups: hardware, software costs, and personnel costs. Extra or derived costs like power expenses, previous studies or cleaning among others have not been taken into account. The hardware costs consist of all the devices acquired or used in this study and are included in the table 11.1 [27]. The software costs include all the programming with a payment license used during the study. The UPC has an agreement with MathWorks so Matlab is not included in the economic analysis. The remaining costs are described in table 11.2. Three different professionals participated in this study, a Biomedical Engineer student (author of the study), a Mechanical Engineer (tutor of this project) and the personnel of Administration and Services of the EEBE. Based on average salaries and social insurance tax in Spain, the personnel costs are shown in table 11.3 [28]. Finally, the total cost of the study is the sum of the three groups (table 11.4).

Hardware costs					
Device	Individual cost (€)	Quantity	Total cost (€)	Depreciation (%)	Final cost (€)
Optitrack Flex 13	1.099	6	6.594	4,2	276,95
Optihub	329	2	658	4,2	27,64
BEL PC	1500	1	1500	4,2	63
Personal Laptop	499	1	499	4,2	20,95
Arduino UNO	25	1	1	4,2	1,01
<b>Total</b>					<b>389,55</b>

Table 11.1. Hardware costs (Own source)

### Software costs

Program	Cost (€)	Time of use (months)	Real cost (€)
Nuitrack	62,34 (perpetual license)	5	3.12
Motive	2.603,13 (annual subscription)	5	1084,64
<b>Total</b>	<b>1087,76</b>		

Table 11.2. Software costs (Own source)

Personnel costs				
Position	Monthly Salary(€)	Work time (h)	Salary(€)	Cost(€)
Mecanical Engineer	2.604,17	600	9.765,64	12.695,33
Engineering student	1.692,71	600	6.347,66	8.251,96
Personeel of Administration and Services	2.517,71	20	314,71	409,12
<b>Total</b>	<b>21.356,41</b>			

Table 11.3. Personnel costs (Own source)

Total costs	
Group	Cost (€)
Hardware	389,55
Software	1.087,76
Personnel	21.356,41
<b>Total</b>	<b>22.833,72</b>

Table 11.4. Total costs (Own source)

The total cost invested for this study is 22.833,72€ plus minor ordinary expenses that are not taken into account.

## 12. References

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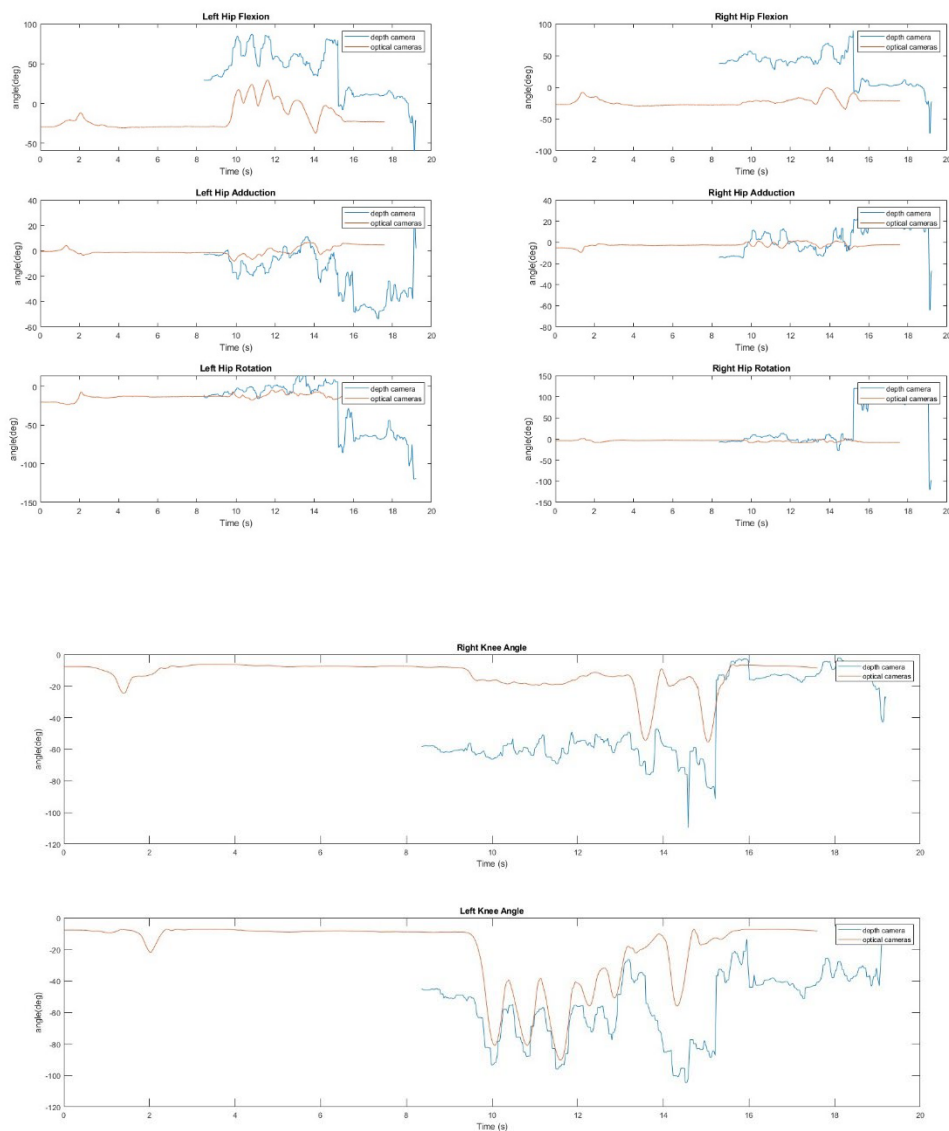




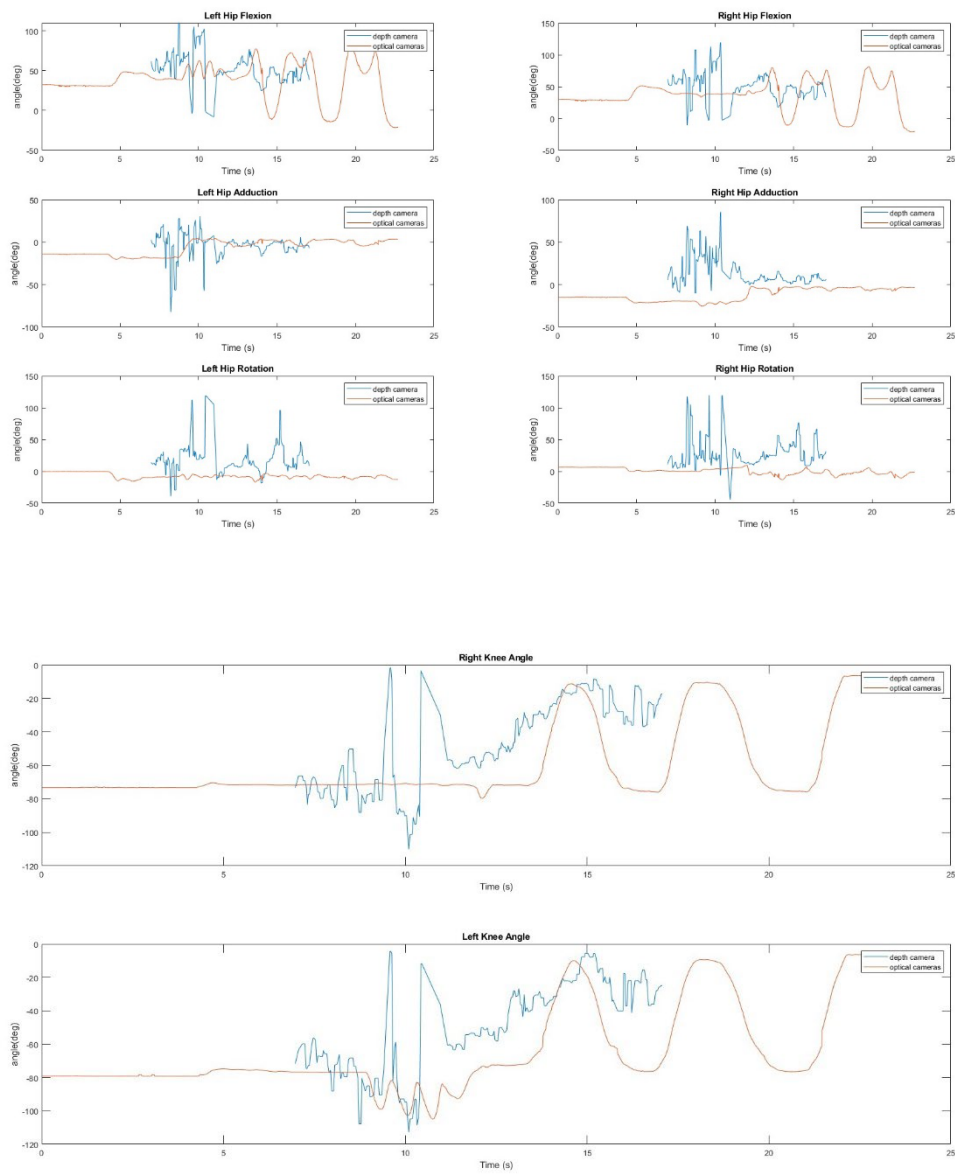
# Appendix

## Comparison plots

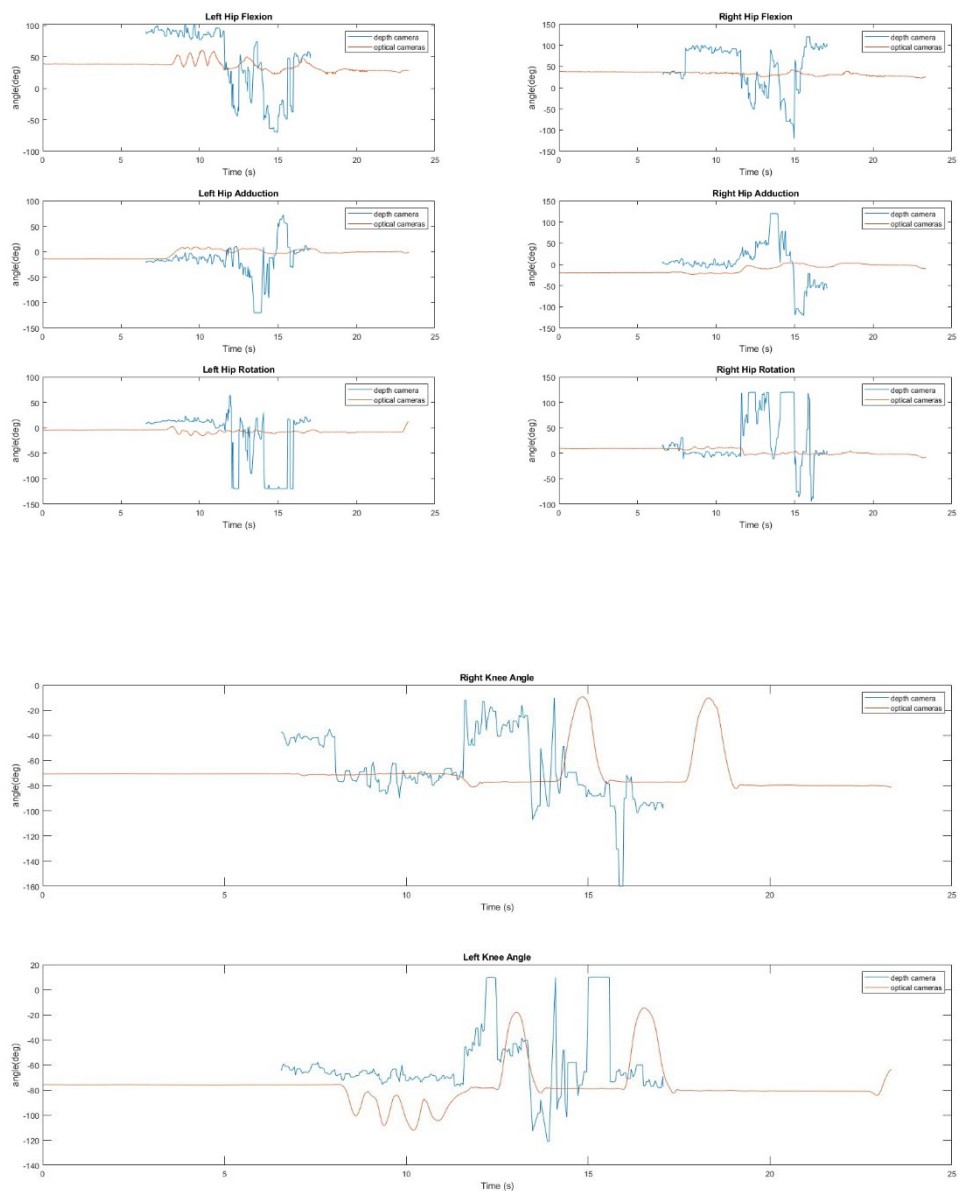
### Exercise 1:



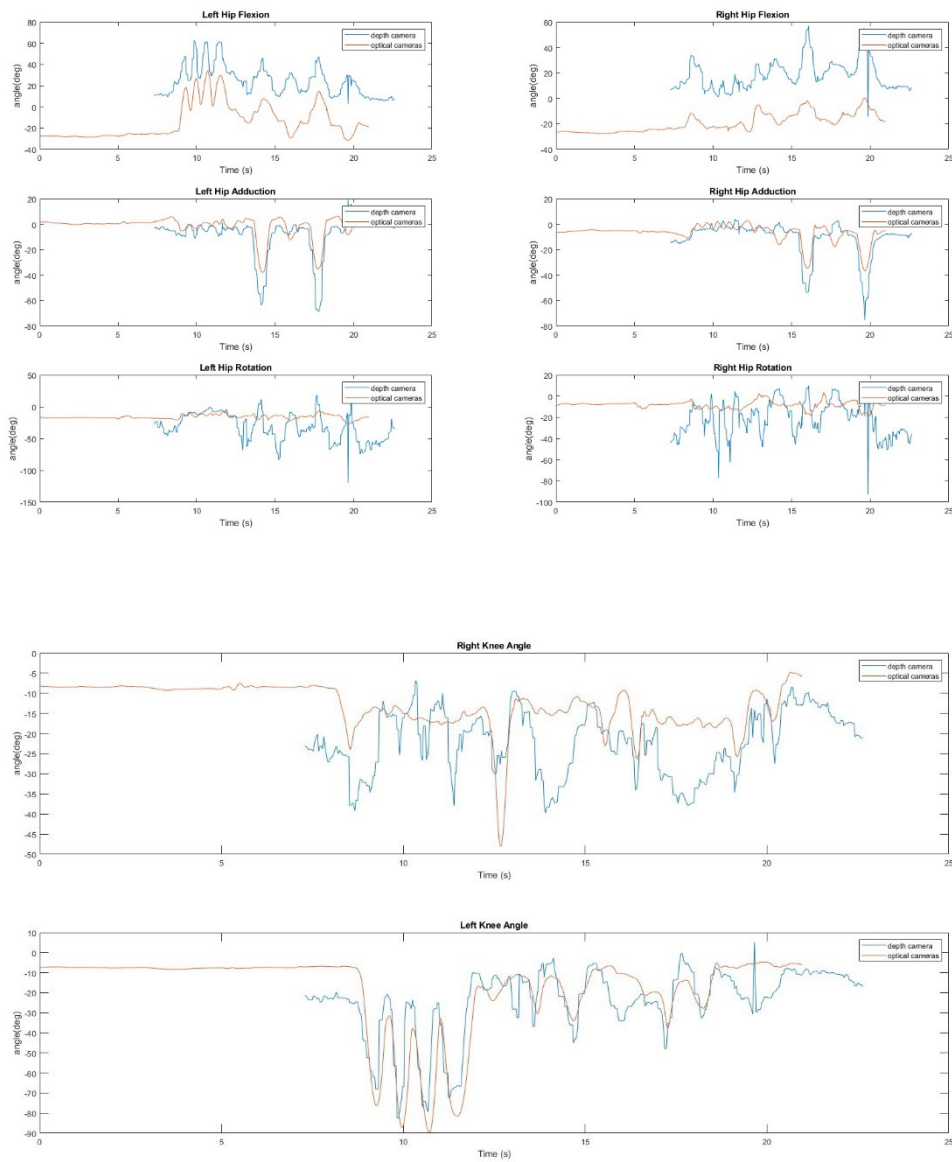
## Exercise 2:



Exercise 3:

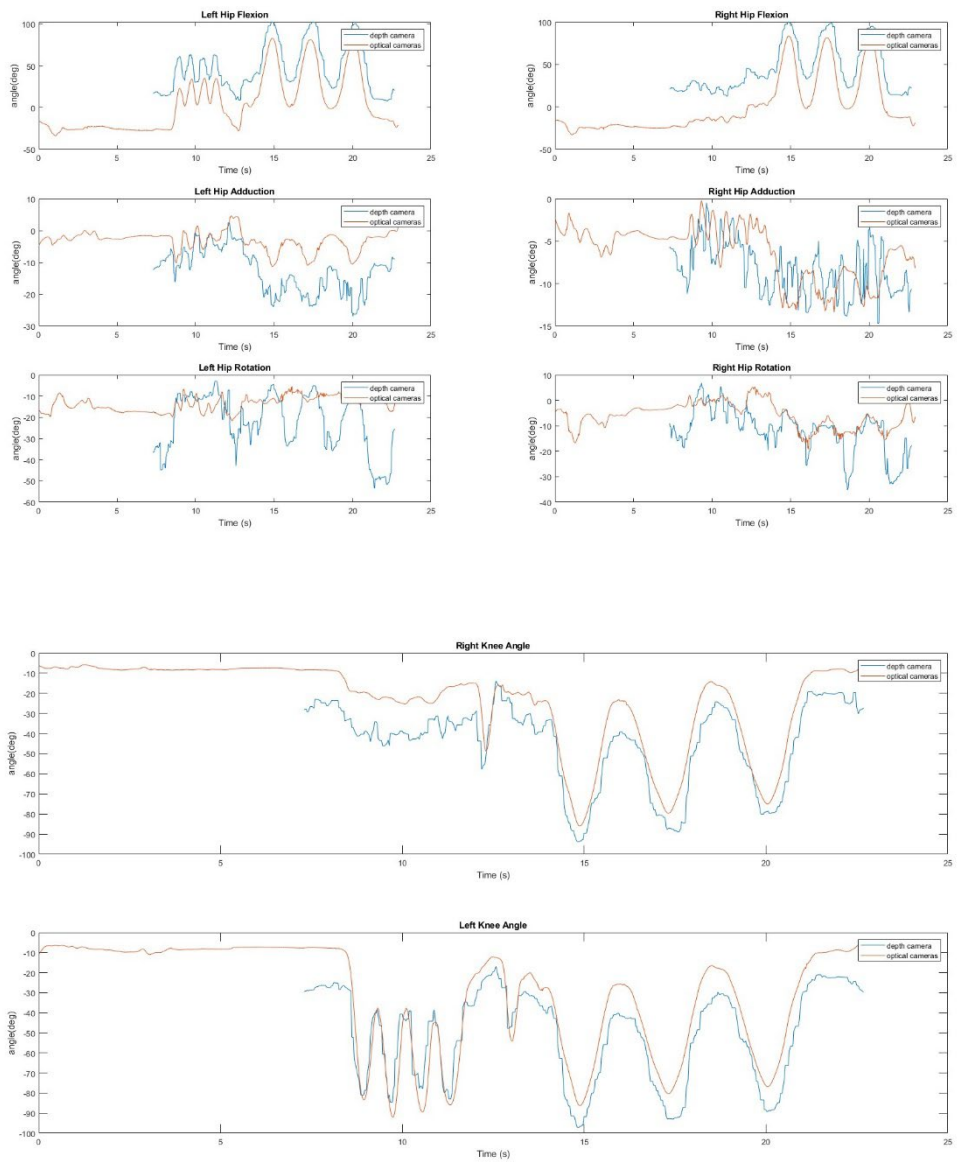


## Exercise 4:

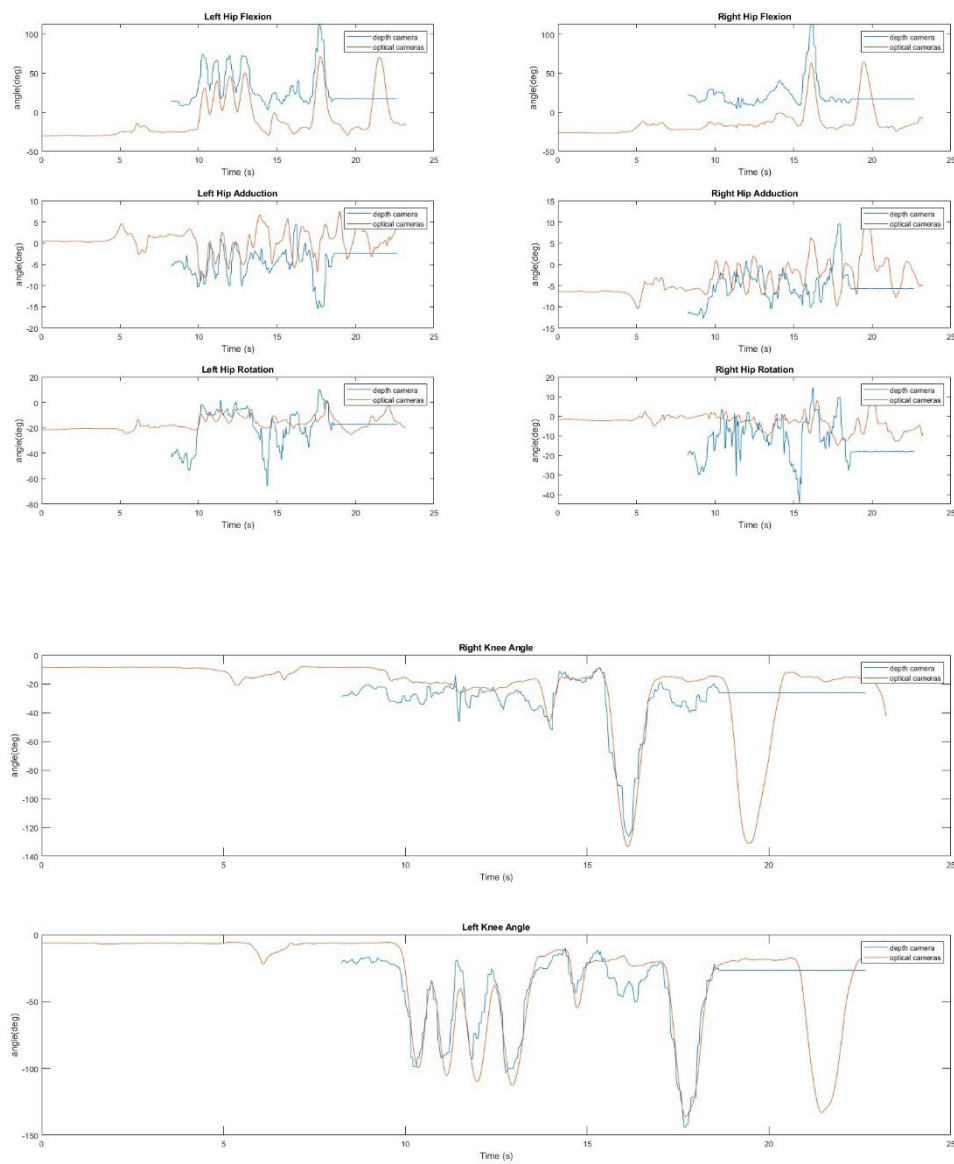




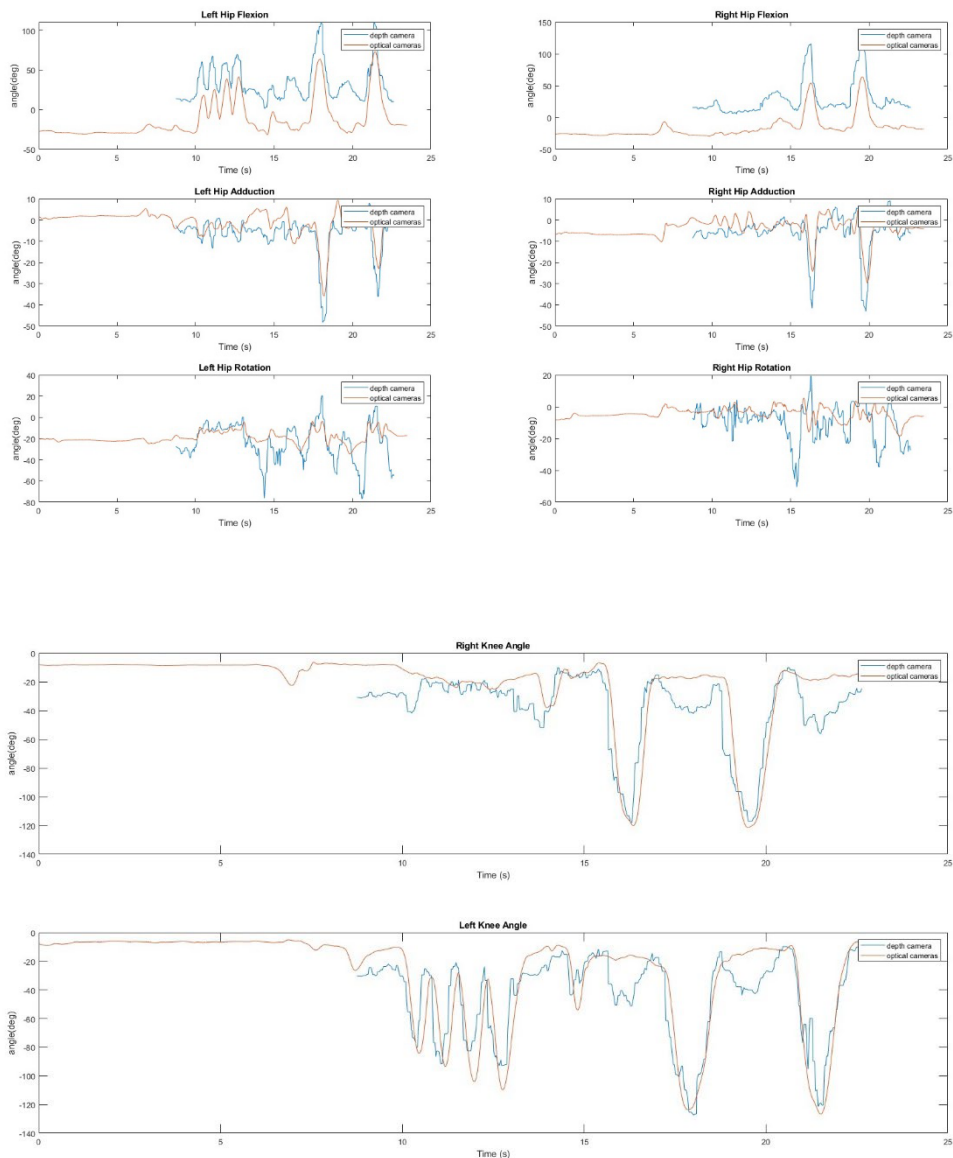
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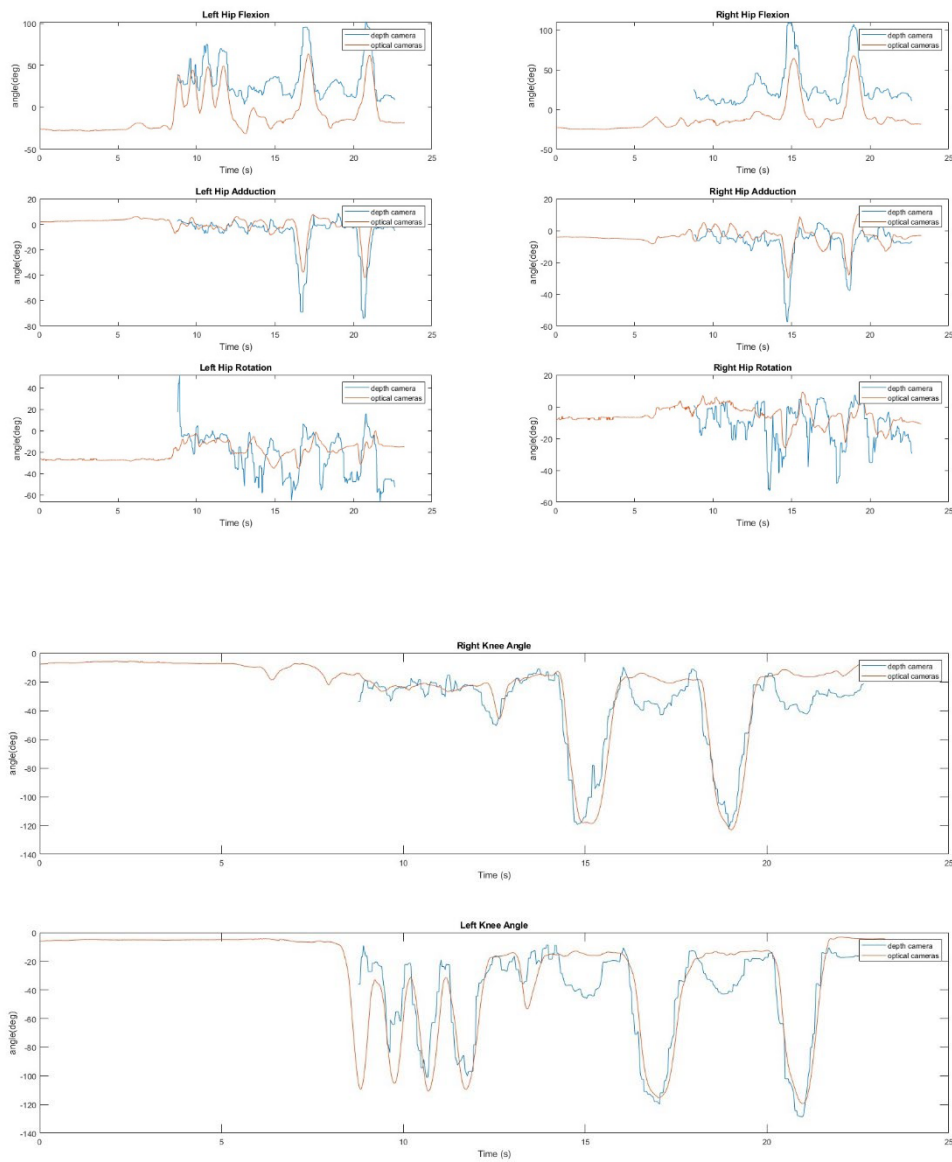
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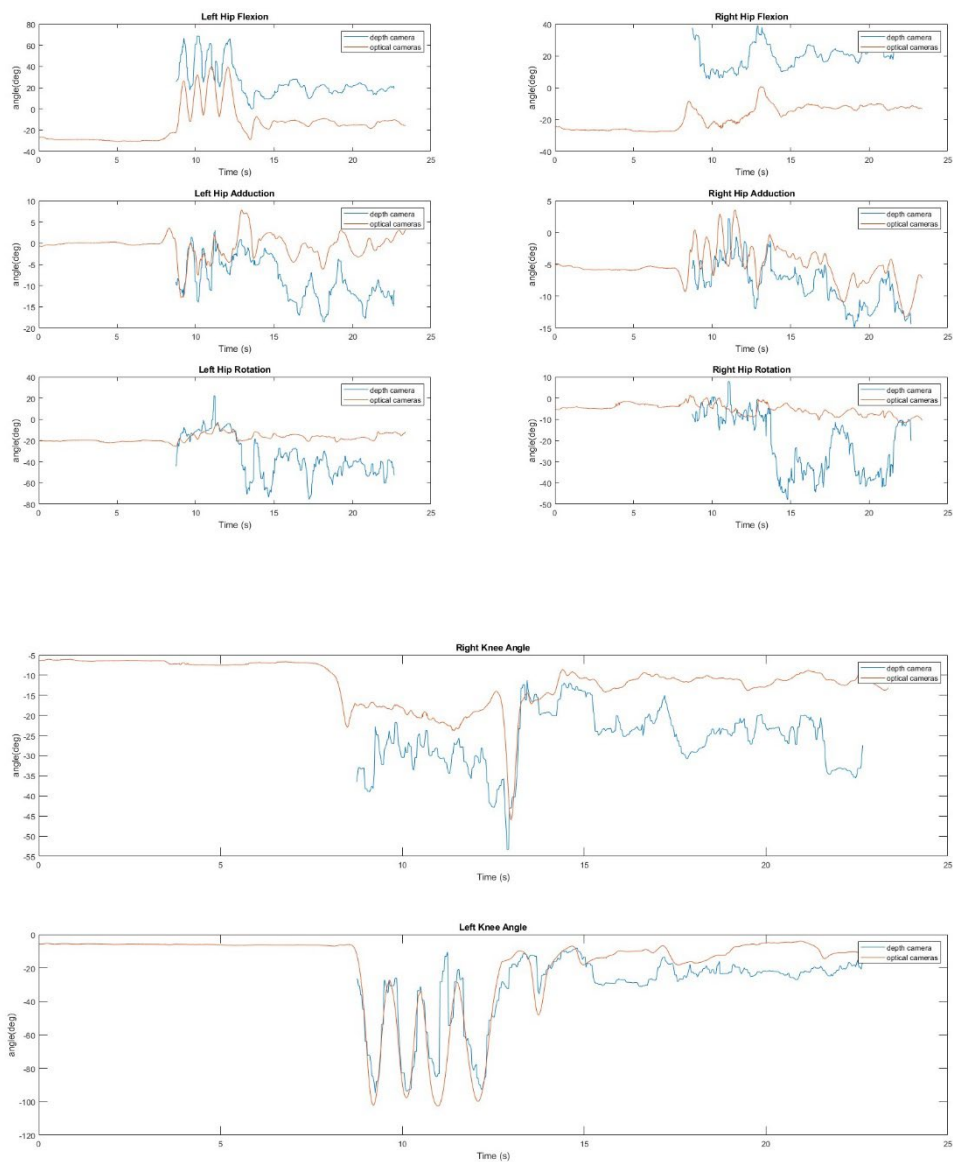
Exercise 7:



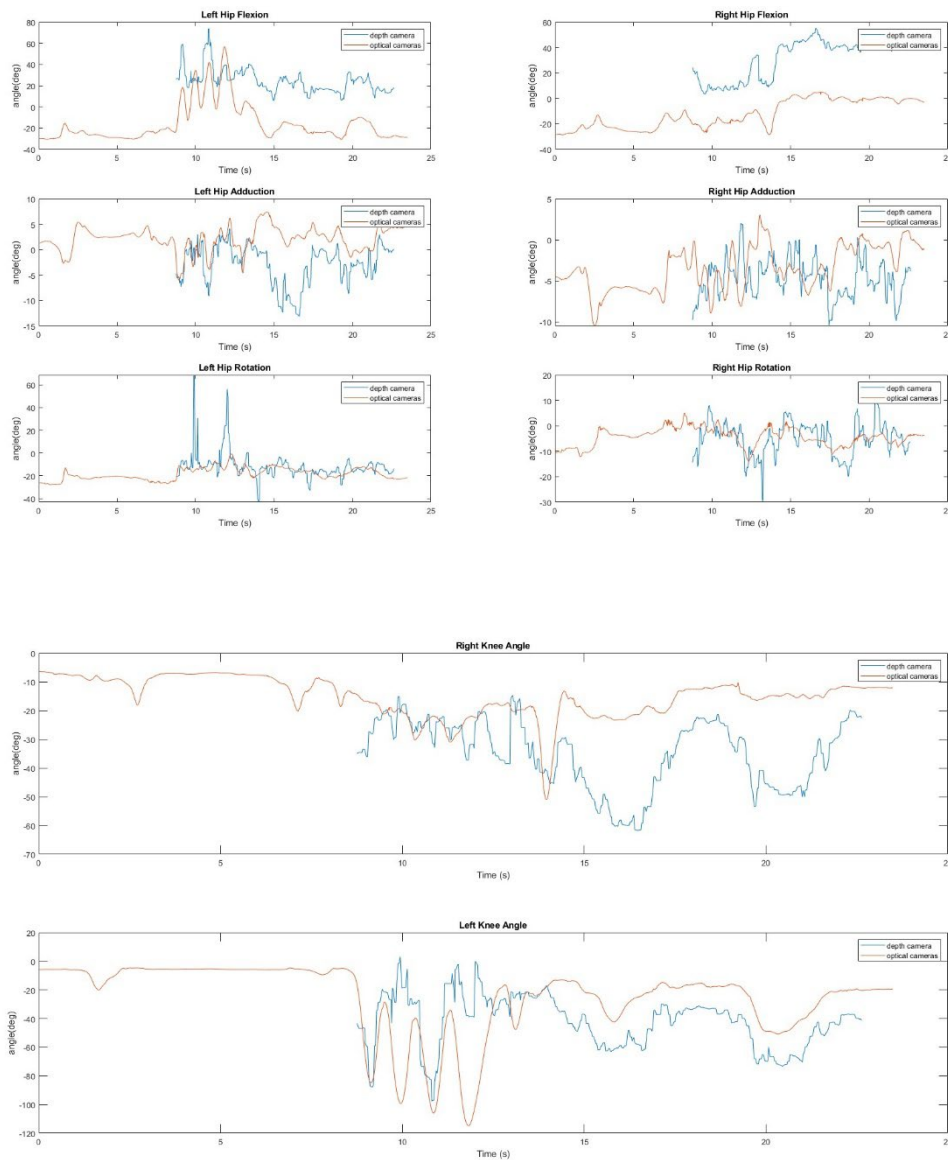
## Exercise 8:



### Exercise 9:



## Exercise 10:



## Correlation coefficient results

Correlation coefficient calculated for each joint and exercise		result	
exercice		right	left
1	hip flexion	0.21	0.77
	hip adduction	0.15	0.34
	hip rotation	0.44	0.06
	knee flexion	0.55	0.66

		right	left
4	hip flexion	0.77	0.8
	hip adduction	0.85	0.89
	hip rotation	0.22	0.19
	knee flexion	0.74	0.8
		right	left
5	hip flexion	0.97	0.97
	hip adduction	0.31	0.75
	hip rotation	0.52	0.05
	knee flexion	0.97	0.93
		right	left
7	hip flexion	0.92	0.86
	hip adduction	0.74	0.81
	hip rotation	0.03	0.55
	knee flexion	0.86	0.87
		right	left
8	hip flexion	0.93	0.82
	hip adduction	0.66	0.86
	hip rotation	0.14	0.19
	knee flexion	0.93	0.84
		right	left
9	hip flexion	0.82	0.91
	hip adduction	0.71	0.44
	hip rotation	0.19	0.48
	knee flexion	0.54	0.87
		right	left
10	hip flexion	0.95	0.71
	hip adduction	0.11	0.21
	hip rotation	0.41	0.72
	knee flexion	0.15	0.14