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Marker-less motion capture for biomechanical analysis using the Kinect sensor

BACHERLOR'S THESIS

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ABSTRACT

Motion capture systems are gaining more and more importance in different fields of research. In the field of biomechanics, marker-based systems have always been used as an accurate and precise method to capture motion. However, attaching markers on the subject is a time-consuming and laborious method. As a consequence, this problem has given rise to a new concept of motion capture based on marker-less systems. By means of these systems, motion can be recorded without attaching any markers to the skin of the subject and capturing colour-depth data of the subject in movement. The current thesis has researched on marker-less motion capture using the Kinect sensor, and has compared the two motion capture systems, marker-based and marker-less, by analysing the results of several captured motions. In this thesis, two takes have been recorded and only motion of the pelvis and lower limb segments have been analysed. The methodology has consisted of capturing the motions using the marker-based and marker-less systems simultaneously and then processing the data by using specific software. At the end, the angles of hip flexion, hip adduction, knee and ankle obtained through the two systems have been compared. In order to obtain the three-dimensional joint angles using the marker-less system, a new software named *iPi Soft* has been introduced to process the data from the Kinect sensor. Finally, the results of two systems have been compared and thoroughly discussed, so as to assess the accuracy of the Kinect system.

TABLE OF CONTENTS

1. INTRODUCTION

1.1. Motivation

The use of motion capture systems is gaining more and more importance in present research. It is used in the field of biomechanics, industries and entertainment. In order to capture different movements of the body, it is required to have an accurate method to capture motion and then record it. Until now the UPC Biomechanics Lab has used maker-based motion capture technologies to capture motions. Although it is a highly accurate method, it also has the disadvantage of the time spent on attaching the markers to the subject. The motivation of this project is to reduce the time consumed in this process and facilitate motion capture. One of the solutions is to implement a marker-less motion capture system based on the Kinect sensor, which will complement the equipment of the Biomechanics Lab at ETSEIB. Moreover, it is an opportunity to discover new technologies, to innovate and to improve the method used before.

1.2. Objectives

Even though the marker-based system is accurate enough to capture either simple or complex motions, the main objective of this project is to assimilate the marker-based results using marker-less system as much as possible. As the two systems have its own algorithm and software system, the exact coincidence of the results will be unachievable. Nevertheless, to achieve similar results within the minimum errors would be the aim of this project. In order to achieve this objective, it is suggested to study several movements of different level of complexity and compare the results obtained by means of both methods. Finally, the conclusions of the work will be drawn and suggestions for further research proposed.

1.3. Scope

The current project will only focus on the kinematic analysis of the results, in other words, only three-dimensional joint angles will be analysed. Moreover, only the pelvis and lower limb segments will be studied in this project. In this project, the official software provided by iPi Soft will be used, so there is no need to program a code to obtain the results from the Kinect sensor.

2. STATE OF THE ART

2.1. Motion Capture

Motion capture is the process of recording the movement of objects or people using sensors and transforming this live performance into a digital performance which can be saved and analysed afterwards. In the 19th century, investigators had already started to research into the methodical studies of human and animal motion, and then the advent of modern computer-based motion capture system provided the ability to capture accurate 3D motion in new and flexible ways [1]. A variety of technologies has been used to meet this objective, including marker-based optical systems, marker-less systems and non-optical systems. Accurate motion capture is essential in several industries ranging from animation and game development to life science and medicine [2].

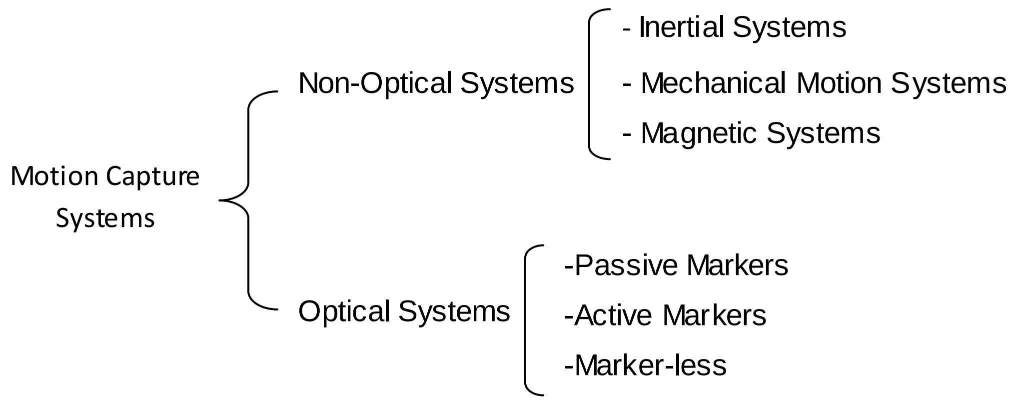
In entertainment, motion capture is being used more and more for 3D animation in films so as to create characters that move realistically in situations that would be impractical or too dangerous for real actors. It is also used for games, it provides the ability to capture 3D motions of the players in order to control the character in the game.

In industrial applications, it is essential for producing product designs that are ergonomically practical and it can be used for measuring and evaluating the performance of industrial robots. There are other applications such as vessel tracking above and under water, aerodynamics tests, automotive development, interior design and control design.

In biomechanics, researchers use motion data to study and observe human performance. By understanding human motion, researchers are able to improve treatment during rehabilitation as well as improve performance for sport applications. For instance, some of the applications are gait analysis, ergonomics and human factors.

2.2. Classification of motion capture systems

Modern motion capture systems have taken a variety of approaches to solve the problem of tracking motion accurately. Broadly, it can be classified into two general categories, optical and non-optical systems. Among the optical systems, the majority of the systems used today are marker-based, however the marker-less system has stand out over the last years. On the other side, the most common of non-optical systems is based on inertial sensors. The scheme below shows the classification of motion capture systems.



2.3. Optical Systems

Optical systems capture the movement from special markers which are attached directly to the surface of the actor's body using proprietary video cameras. The subject is surrounded by calibrated cameras, each camera extracts 2D coordinates information of each marker during the capture at the camera reference. The set of the 2D data captured by independent cameras is then analysed and the result generates the 3D coordinates of the markers [4]. Moreover, special computer algorithms are designed to allow the system to analyse multiple streams of optical input.

Optical systems are frequently applied to obtain kinematic input for musculoskeletal model and can be classified into marker-based and marker-less sensors. There are two main technologies used in marker-based sensors: passive and active.

2.3.1. Passive optical system

Passive optical system use markers made of retro-reflective material to reflect light that is generated near the cameras lens. Markers are illuminated using Infra-red (IR) lights mounted on the cameras. The markers are attached directly to the skin or surface of the subject. (*Figure 2.3.1*)

Figure 2.3.1 Passive markers [www.qualisys.com]

2.3.2. Active optical system

Active optical system use pulsed-LED markers (reflectors) which can emit IR light rather than reflect. This system triangulates positions by illuminating one LED at a time very quickly or multiple LEDs with software to identify them by their relative positions. (*Figure 2.3.2*)

Figure 2.3.2 Active Markers [www.sfdm.scad.edu]

2.3.3. Marker-less motion capture

In spite of the fact that marker-based motion capture is accurate, it is a time-consuming process to attach correctly each marker in the required position. As a consequence, marker-less motion capture technology has been developed rapidly. The most notable among these marker-less systems is *Microsoft's Kinect* (*Figure 2.3.3*).

Kinect is a motion sensing input device which enables to capture a subject's movements without the need of markers. Kinect is used mainly as a gaming product, but now it is also used in biomechanical fields because of its simplicity. It is an active vision system that captures depth and colour images simultaneously and provides full-body 3D motion capture and facial recognition by using an infra-red projector and a special microchip [8]. Apart from Kinect, there are also other products which use marker-less systems, such as SoftKinetic [25], PrimeSense [24] and Organic Motion [3].

As for SoftKinetic, it is a company which develops gesture recognition hardware and software for real-time range imaging (3D) cameras such as time-of-flight cameras. It is a camera system that resolves distance based on the speed of light, measuring the time of flight of a light signal between the camera and the subject for each point of the image. PrimeSense, as SoftKinetic, also provides gesture recognition using synchronized image stream and translates them into digital information. The algorithms of PrimeSense utilize the depth, color, IR and audio information received from the hard device, which enable them to perform functions such as hand locating and tracking; user segmentation; user skeleton joint tracking and more. Finally, the Organic Motion is a company which provides professional marker-less motion capture systems for game development and animation, life science and military training and simulation. The systems use advanced computer vision technology to generate highly accurate 3D tracking data in real-time. One of the most revolutionary marker-less motion capture products of Organic Motion is BioStage. It consists of a space surrounded by several marker-less motion capture cameras over the stage, due to this, it is capable to capture accurately and efficiently a full 3D view. Besides this, it is accessible and practical for more than one people in the same space. Additionally, BioStage maker-less motion analysis system requires no setup or calibration downtime between subjects, and as a result, it increases the speed and efficiency of the calculations, allowing to develop more simulations.

Figure 2.3.3 Kinect [www.microsoft.com]

2.4. Non -Optical Systems

There are three types of non-optical systems: inertial, mechanical and magnetic. The most common ones are inertial sensors. The difference between non-optical systems based on inertial sensors and optical systems is that the former ones measure rotation, acceleration and flexion instead of relative displacement measured by the latter ones. This has the advantage of not requiring complex computer vision technology to gather accurate data about relative movement.

2.4.1. Inertial Motion Capture

Measurement sensors such as accelerometers and gyroscopes are commonly used for inertial motion tracking. One of the products on the market is *Xsens MVN Inertial Motion Capture* [16]; it consists of inertial sensors attached to the body by a lycra suit resulting in a flexible and portable motion capture system (*Figure 2.4.1*). Video cameras are not necessary in this case as the motion data of the inertial sensors is transmitted wirelessly to a computer. MVN inertial motion capture measures three-dimensional (6 degree of freedom) position and orientation of body segments in a global coordinate system. Each sensor unit contains 3D gyroscopes, 3D accelerometers and 3D magnetometers. Gyroscopes measure angular velocity which is integrated over time to find segment orientation. Accelerometers measure linear acceleration which is twice integrated to find segment position [17].

Figure 2.4.1. Xsens Inertial Motion Capture Suit [www.xsens.com]

2.4.2. Mechanical motion systems

Mechanical motion capture systems track directly body joint angles using a skeletal-like structure attached to subject's body and as the performers move so do the articulated mechanical parts, measuring the performer's relative motion. These systems consist of electrogoniometers, a sensor system made up of potentiometers or transducer technology designed to estimate joint angles when positioned close to a joint on the subject's body. The measures of this equipment are not affected by magnetic fields or undesirable reflections, but generally significantly obstructive. In comparison to inertial sensors or optical-based motion sensors, the mechanical motion capture system allows for direct measurement of movement, which means that the subject can move around more freely in a large environment without any movement being out of view by a central camera system, nor is the capture system affected by reflective light [27].

A wireless mechanical motion capture sensory system on the market is the Gypsy 5 engineered by *Meta Motion* (*Figure 2.4.2*). The Gypsy systems capture analogue data from the potentiometers and convert it into digital values. Furthermore, the data drives a skeletal representation of the performer's skeleton in real-time, in response to the performer's motions.

Figure 2.4.2 Mechanical motion capture suit [www.metamotion.com]

2.4.3. Magnetic systems

Magnetic systems utilize sensors placed on the body to measure low-frequency magnetic field generated by a transmitter source. The sensors and source are cabled to an electronic control unit that correlates their reported locations within the field. The sensors report position and rotational information. Performer wears an array of magnetic receivers which track location with respect to a static magnetic transmitter. Magnetic motion system usually involves using 6 to 11 sensors around the joint to a subject's body where each sensor works to produce measurements on the position and rotation of the corresponding joint. It is built with transmitters that can allow for up to six degrees of freedom, which offers the subject to be slightly more creative with movements [27].

3. LABORATORY EQUIPMENT

All the data will be taken in the UPC Biomechanics Lab at ETSEIB. The equipment used for this project will be, on the one side, an optical system using video cameras and passive markers and on the other side, a marker-less system using Microsoft Kinect. In the next chapter, both hardware and software will be described in detail.

3.1. Marker-based Optical Systems

In order to take the measures by means of passive optical systems which has been mentioned previously in the chapter state of art, the Biomechanics Lab provides a system using 18 OptiTrack™ [5] cameras of FLEX: V100 R2 model from Natural Point Company© (*Figure 3.1.1*) and passive markers attached to the surface of the subject studied. The OptiTrack Flex: V100 camera offers integrated image capture, processing and motion tracking in a unit. It uses IR long pass filter and captures 100 frames per second. Moreover, by maximizing its 640x480 VGA[1] resolution through advanced image processing algorithms, the Flex camera can also track markers down to sub-millimetre movements with repeatable accuracy. The cameras are connected to the computer through two hubs and then a commercial software named ARENA© is used to display the captured data.

Figure 3.1.1. Natural Point OptiTrack™ Cameras. FLEX. V100 R2
*[*www.naturalpoint.com/optitrack]

[1]VGA: Video Graphics Array. A standard resolution (size) for camera sensors, displays, photos, and videos.VGA size is 640 pixels wide by 480 pixels tall (or vice-versa in portrait orientation).

Each of the cameras, consists of 26 IR LEDs, emits light to the passive markers which reflect the light back to the cameras. These reflected lights are detected by the cameras within a frequency of 100Hz. As a consequence, the coordinates of each marker are obtained in a plane situated in a determined distance where all the cameras are capable to reach. The Biomechanics Lab is provided with a system using 18 OptiTrack V100 IR cameras placed around the lab, surrounding the space where experiments are taken. In the *Figure 3.1.2*, it can be seen the arrangement of these 18 cameras, 12 of which are virtually hanging from the ceiling, arranged at a superior level, while the remaining 6 are found at a slightly lower level, about 1,5 metres below.

After capturing the motion, the software ARENA [29] processes the motion using data of all the cameras and manages to adjust the data all together to obtain 3 dimensional trajectories of the markers. Subsequently, this trajectory data are saved so as to be analysed within the software MATLAB. Finally, the MATLAB file will be processed using a software system named OpenSim [28] to obtain kinematic data and create models of skeletal structures. This procedure will be explained in full detail in the next chapter.

Figure 3.1.2. Biomechanical laboratory

3.2. Kinect System

As it is described before, the Kinect system is a marker-less motion capture system. Thus far, the Biomechanics Lab at ETSEIB has been using the marker-based systems and all the equipment was already installed. On the contrary, the Kinect system is a new system that has not been investigated before in this Lab. Consequently, all the equipment should be bought and installed for this project from the beginning.

The equipment of Kinect systems consists of two parts: one is the hardware and the other the software. The former part will deal with the recording of the movements, while the latter part will manage to process all the data and extract information from the recording. All the components required of each part will be specified in the following section.

3.2.1. Hardware

In nowadays Market, there is the Microsoft Kinect for Windows [8] (*Figure* 2.3.3) and the Kinect for Xbox 360 [9] (*Figure 3.2.1*). Although people think that they are the same, there are several differences between them. Kinect for Windows offers several features that are not enabled when using a Kinect for Xbox 360. For example, Kinect for Windows enables the camera to capture objects as close as 40 centimetres in front of the device without losing accuracy or precision and also provides extra configurations such as brightness, exposure, etc. Furthermore, another difference between them is that the Kinect for Windows can be sold separately which costs about 220€ and the other one, which costs 145€, can only be sold with Xbox's other gaming products. In this project, it has been used one Kinect for Xbox 360 and one Kinect for Windows to capture motion.

After informing the difference between one Kinect system and dual Kinect system, the latter system was chosen for this project, because it permits to track 360 degrees of rotation while the other one can only track simple motions without rotation. Moreover, the dual Kinect system is more accurate than one Kinect system. Subsequently, three aspects of the Kinect will be explained in detail, namely technical specification, coordinate spaces and environment.

a) Technical Specification

Kinect sensor, which has been mentioned before, is a colour-depth camera, as it can be seen in *figure 3.2.2,* the Kinect sensor includes the following 4 components. The number 1 indicates two 3D depth sensors which can track the subject body within the play space. The number 2 indicates a RGB (red, green, blue) camera which helps identify the subject and takes pictures and videos. Along the bottom of the front edge of the Kinect sensor, where indicates the number 3, is situated an array of microphones which are used for speech recognition and chat. However, this function will not be used as the aim of the project is to capture only the motion. The last component (number 4) is a motorized tilt in the base which can automatically tilts the sensor head up and down when needed.

Kinect sensor's frequency is 30 FPS (frames per second) and the resolution of the camera is 640x480 pixels. The depth sensor consists of an IR emitter which emits infrared light beams and then the IR beams are reflected back to the depth sensor. Afterwards, the depth sensor reads this information and converts it into depth data measuring the distance between the object and the sensor [15].

Figure 3.2.1. Microsoft Kinect from Xbox 360 [http://www.xbox.com/]

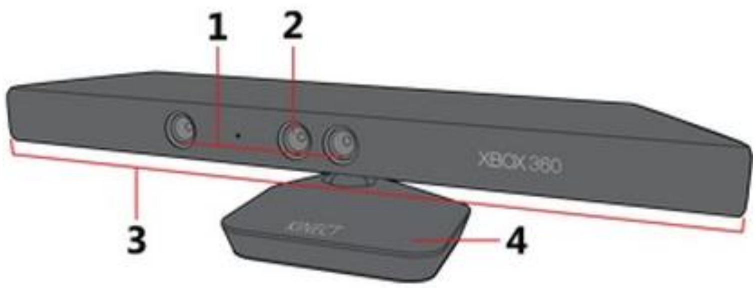


Figure 3.2.2. Kinect Sensor Components [http://support.xbox.com/]

b) Coordinate Spaces

The Kinect sensor captures colour, depth and skeleton data at the same time. This section will explain briefly three coordinate spaces, namely colour space, depth space and skeleton space [11].

Firstly, the colour space consists of a colour image which contains the red, green and blue value of a single pixel at a particular coordinate. Secondly, the depth space is when the depth sensor captures a greyscale image which contains distance information from the camera to the object. The coordinates of a depth frame do not represent physical units in the space; instead, they only represent the location of a pixel in this frame.

The depth sensor has two depth ranges, namely the default range and the near range. The former range detects distances from 800 mm to 4000 mm and the latter from 400 mm to 3000 mm. *Figure 3.2.1.1* illustrates the sensor depth ranges in meters. The default range is available in both the Kinect for Windows sensor and the Kinect for Xbox 360 sensor while the near range is only available in the Kinect for Windows sensor. There are 4 ranges which is the "unknown", the "too near", the "too far" and the "normal values". The "unknown" value means that no object is detected; the "too near" value means that an object is detected in a near distance so the sensor is unable to provide a reliable measurement and the "too far" value means that an object is detected, but too far to rely on this measurement.

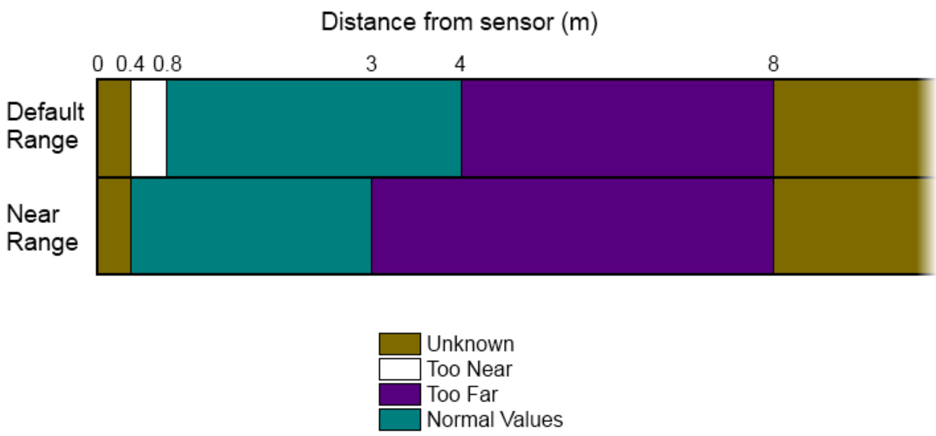


Figure 3.2.1.1. Depth Space Range [http://msdn.microsoft.com/en-us/library]

Finally, the skeleton space is when the depth image captured by Kinect is processed into skeleton data which contains 3D position data of human skeletons for up to two visible objects in front of the sensor. The position of each joint is stored as (x, y, z) coordinates which are shown in the *figure 3.2.1.2*. In this figure, it can be seen that the positive z-axis extends in the direction in which the Kinect is pointed.

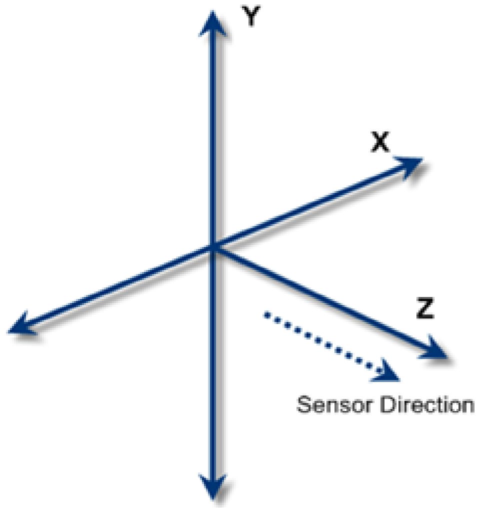


Figure 3.2.1.2.Skeleton Space Coordinates [http://msdn.microsoft.com/en-us/library]

c) Environment

In order to capture reliable measurements from Kinect, it is important to fulfil several specifications of the environment. For a single o dual Kinect system configuration, the minimum space required is 3 by 3 metres and the capture area is about 2 by 2 metres. The height of the Kinect from the floor should be between 0,5 meters and 1 metre [13].

Figure 3.2.1.3 shows the slide view of the space where the experiments take place. Two cases have been represented: one case is to capture full length body, in this case the object should be positioned 2,5 metres away from the Kinect; another case is to capture full length with hands up, this time 3,2 metres is needed between the Kinect and the object so as to capture the motion. *Figure 3.2.1.4* represents the top view of the environment and shows the width of the visible area for the two cases.

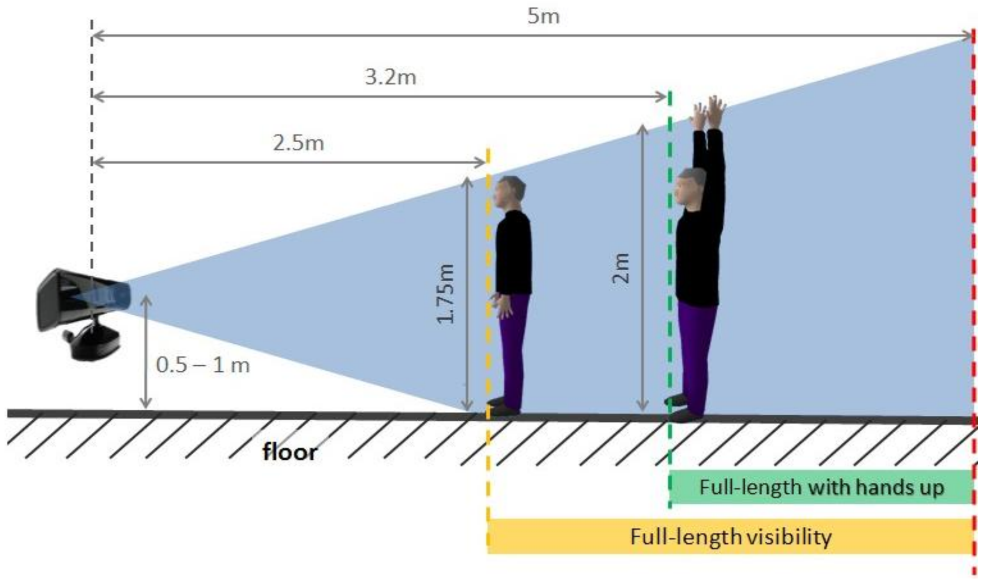


Figure 3.2.1.3. Slide View [http://ipisoft.com/]

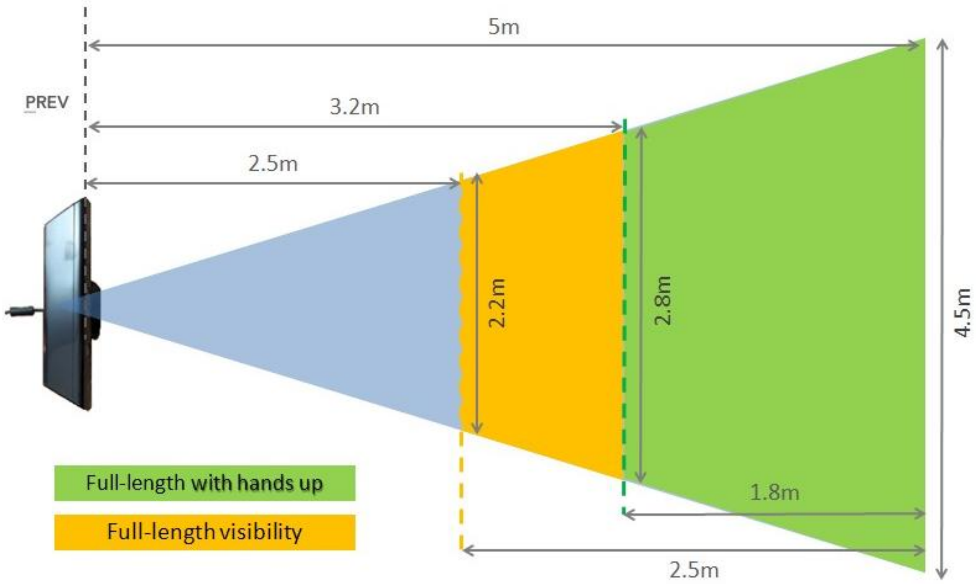


Figure 3.2.1.4. Top View [http://ipisoft.com/]

3.2.2. Software

One of the most important parts of this thesis is the use of the marker-less motion capture software named ***iPi Soft-Motion Capture™***.[7] This software supports 1 or 2 Kinect cameras or 3 to 8 Sony PlayStation Eye cameras to track 3D human body motions and produce 3D animation. There are 3 different editions: the *Express Edition* which supports only one Kinect; the *Basic Edition* which supports dual Kinect system and the *Standard Edition* which also supports dual Kinect system but includes all high-end features and the possibility of tracking multiple persons. As in this thesis is going to use dual Kinect system to capture motion of one object, the Basic Edition is the proper software to process the data. This Basic Edition includes iPi Recorder and iPi Mocap Studio, whose functionality will be explained in detail. Furthermore, the software named iPi Biomech which is an iPi Soft add-on tool for biomechanical analysis of human motion has also been installed. In the following sections, the three tools are presented in detail [6].

a) iPi Recorder

This is a free software provided by iPi Soft for capturing, playing back and processing videos recorded from multiple cameras and depth sensors. As it can be seen in the *figure 3.2.2.1*, the motion captured is represented in colour-depth mode from two Kinect sensors on one screen. Moreover, the captured videos have the effect of mirror which is useful for front-facing cameras during recording. On the up-right corner of each sensor screen there are the original videos of the motion without colour-depth effect. After recording the videos, they are saved in ***.iPiVideo*** file format which can only be played by iPi Soft products [6].

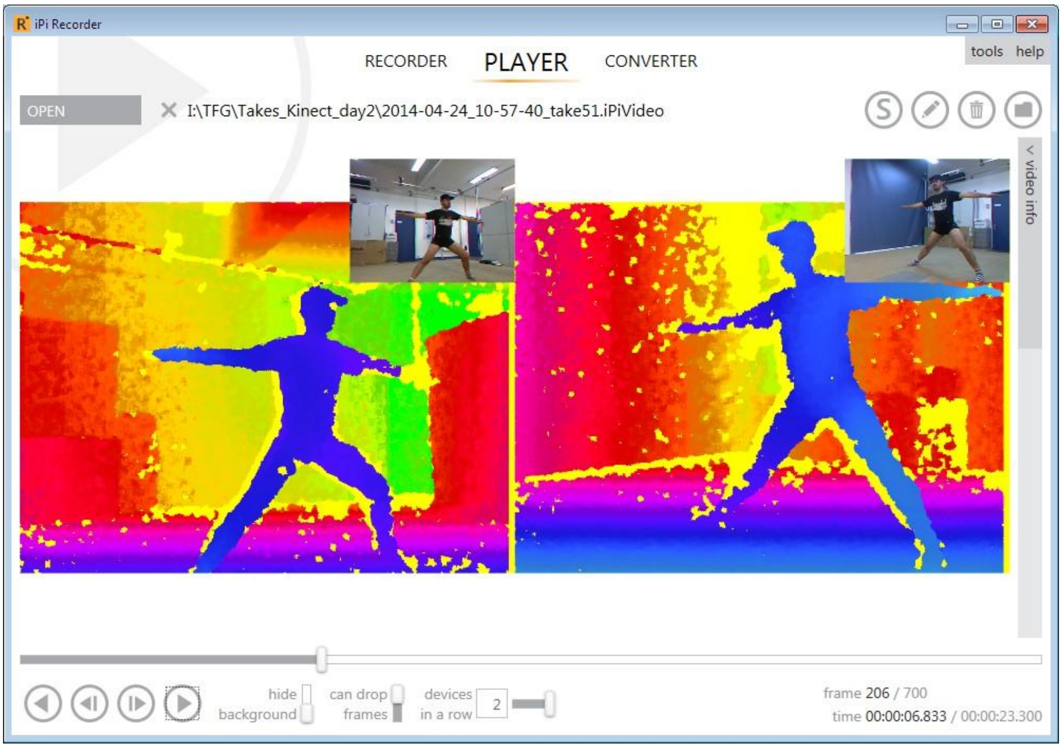


Figure 3.2.2.1. iPi Recorder [http://ipisoft.com/]

b) iPi Mocap Studio

This software program is provided by iPi Soft for tracking objects' motion by analyzing multi-camera video recordings. iPi Mocap Studio processes the videos recorded from iPi Recorder and produces a skeleton animation afterwards.

The *figure 3.2.2.2* shows the screen of the tracking process of iPi Mocap Studio. On the left side of the *figure 3.2.2.2*, the video captured by iPi Recorder is shown. On the right side, there are several sections with different functionality which are export, batch, biomech, scene, actor, tracking and pose. The most important section is the tracking section where a skeleton animation of the original video will be generated. *Figure 3.2.2.3* shows the commands of the tracking section. There are 4 main stages in this section: firstly the object should be refit by an adequate model skeleton using the button "Refit Pose"; secondly, the motion captured will be tracked using the "Track Forward" button; once the tracking is performed on all the video, it can be refined in order to clean out tracking errors (optional); finally, the post-processing stage helps to suppress unwanted noise and preserves sharp, dynamic motions.

After the whole video is converted into a skeleton animation, it can be applied to other software where a humanlike character can be represented. For this reason, it can be exported into different formats, such as FBX, BVH, DMX and SMD [6].

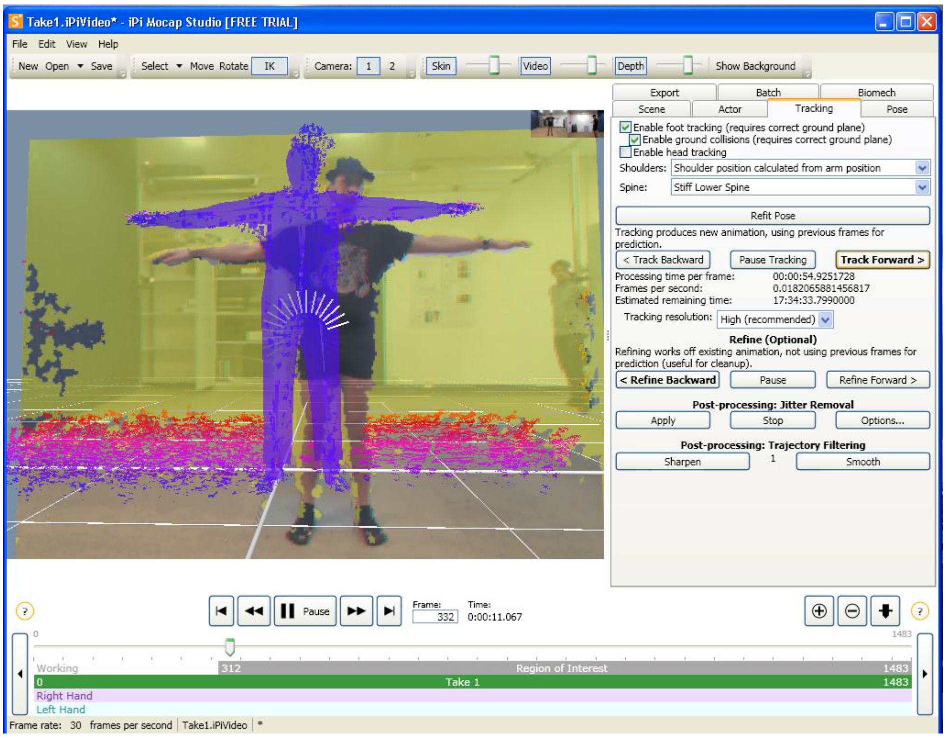


Figure 3.2.2.2. iPi Mocap Studio Screen

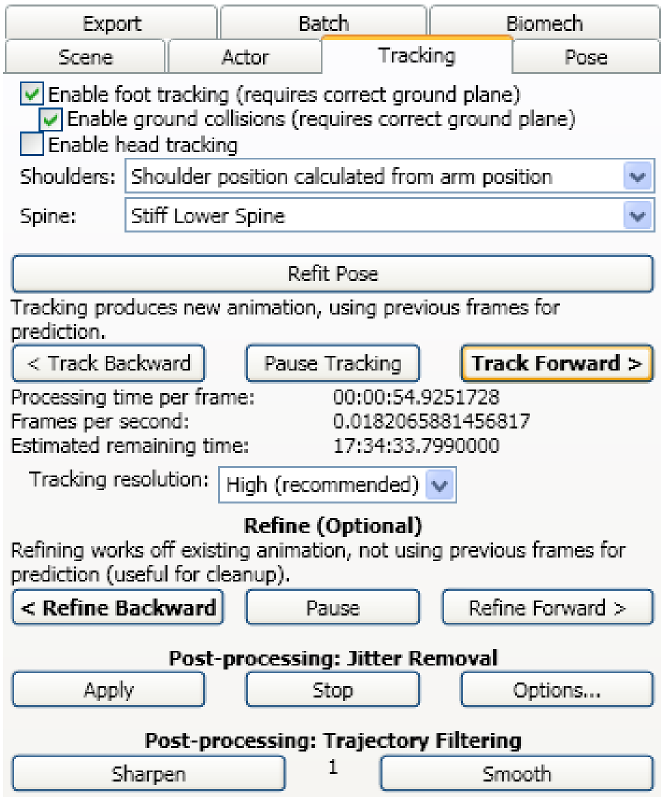


Figure 3.2.2.3. iPi Mocap Studio-Tracking Section

c) iPi Biomech Add-On

iPi Biomech is a tool provided by iPi Soft for in-depth biomechanical analysis of human motions. This software includes visualization of motion capture tracking data from iPi Mocap Studio. It can be used for three fields, namely gait analysis and rehabilitation, sports motion analysis and research in 3D human kinematics [14].

Figure 3.2.2.4 shows all the commands in the Biomech section. Biomech provides linear and angular quantities for selected bones. As for linear quantities, it provides position coordinates velocities and accelerations. Moreover, the coordinate system can be absolute (relative to floor), relative to parent joint or relative to centre of mass. As for angular quantities, it provides Euler angles, angular velocities and angular accelerations. The coordinate systems for angles can be absolute or relative to parent joint. Furthermore, it can plot all the values of selected quantities for each selected bone. Finally, the bones motion data can be exported in EXCEL or MATLAB formats.

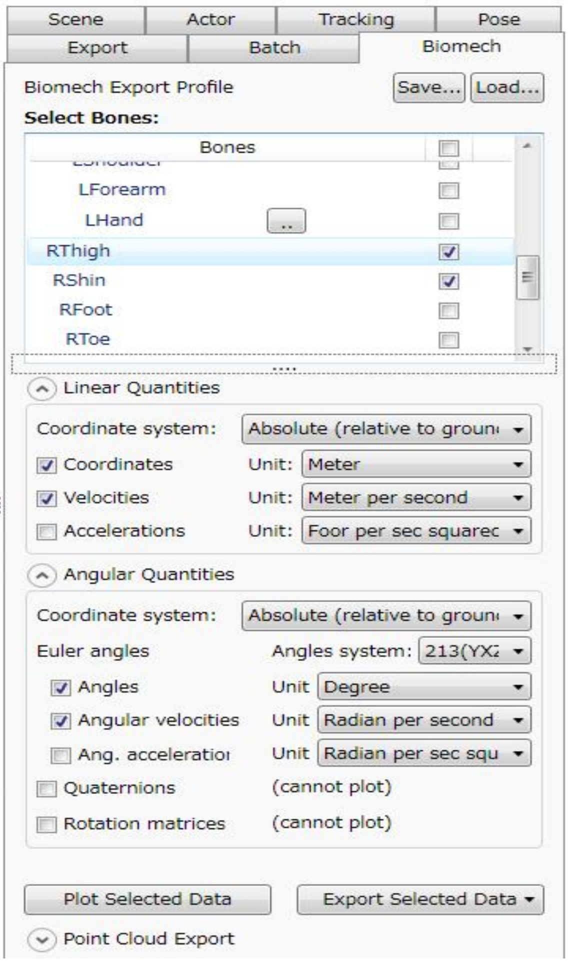


Figure 3.2.2.4. iPi Biomech commands [http://wiki.ipisoft.com]

4. METHODOLOGIES OF BIOMECHANICAL ANALYSIS

The current project involved capturing several motions using Kinect systems and marker-based systems so as to compare the accuracy of the former relative to the latter system. In order to obtain data from the same movements, these were captured using both systems at the same time, in other words, the two systems started to record motions simultaneously when the actor performed the motion. The purpose of this project is to analyse the kinematic results of three lower limb segments: thigh, shank and foot.

The study consists of the analysis of three kinds of motions which were walking, rising legs and squatting. Two takes were captured in this project: in the first take, the subject, a 1,80m boy, did a sequence of slow moments of rising legs and walking in circle; in the second take, the subject walked in circle with a higher velocity, did one squat and then raised his legs up and down. In the following sections, the methodologies for capturing these motions will be explained in detail separately.

4.1. Kinect System

a) Position and Calibration

Before starting to capture the motion, the two Kinects should be positioned in a certain way so as to achieve the optimal workspace dimensions. According to the manual of iPi Soft, the position two Kinects should be as in *figure 4.1.1*. Accomplishing this specification, each Kinect Sensor was put on a chair at the same level (0,5m from floor) forming 90º one to the other. In other words, one Kinect takes the front view of the subject and the other one takes the lateral view of it (*Figure 4.1.2*). Subsequently, the Kinect Sensors were calibrated by recording a video with a rectangular flat board using iPi Soft recorder. The flat board used was 1m x 1.5m which was the recommended size [13].

The aim of making this calibration video is to compute accurate camera positions and orientations for further motion captures. The subject should hold the flat board and moving in the detectable space. While making this video, it is important that the flat board is in blue in both sensors (*Figure 4.1.3*) , in order words, if the image captured of the flat board is in blue that means a good capture and if it is in yellow then no depth data is detected. As it can be seen in *figure 4.1.3*, the flat board was in blue in the both sensors which means a good calibration. Once the camera system has been calibrated, the sensors should not be moved for subsequent video shoots. After recording the calibration video, it was processed in iPi Mocap Studio, when the process was finished the scene was saved as a calibration project which will be used in every action project.

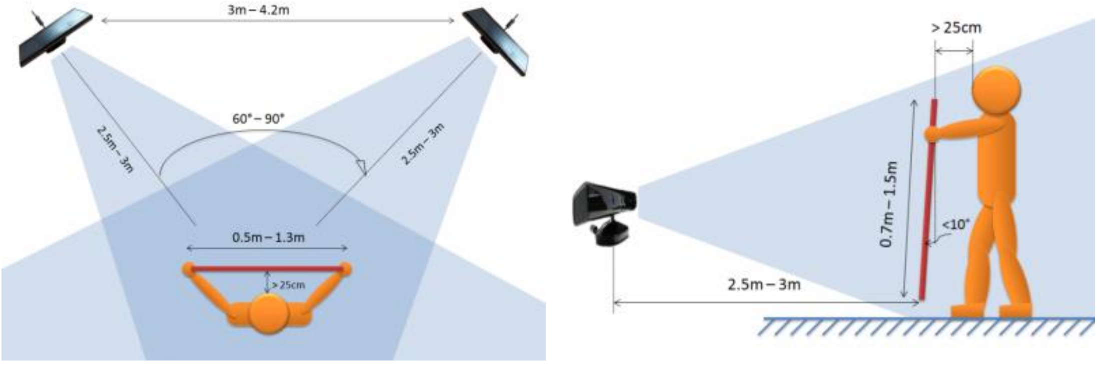


Figure 4.1.1. Position of the Kinects and the subject with the flat board. [http://wiki.ipisoft.com]

Figure 4.1.2. Kinect Position for the capturing in Biomechanics Lab at ETSEIB

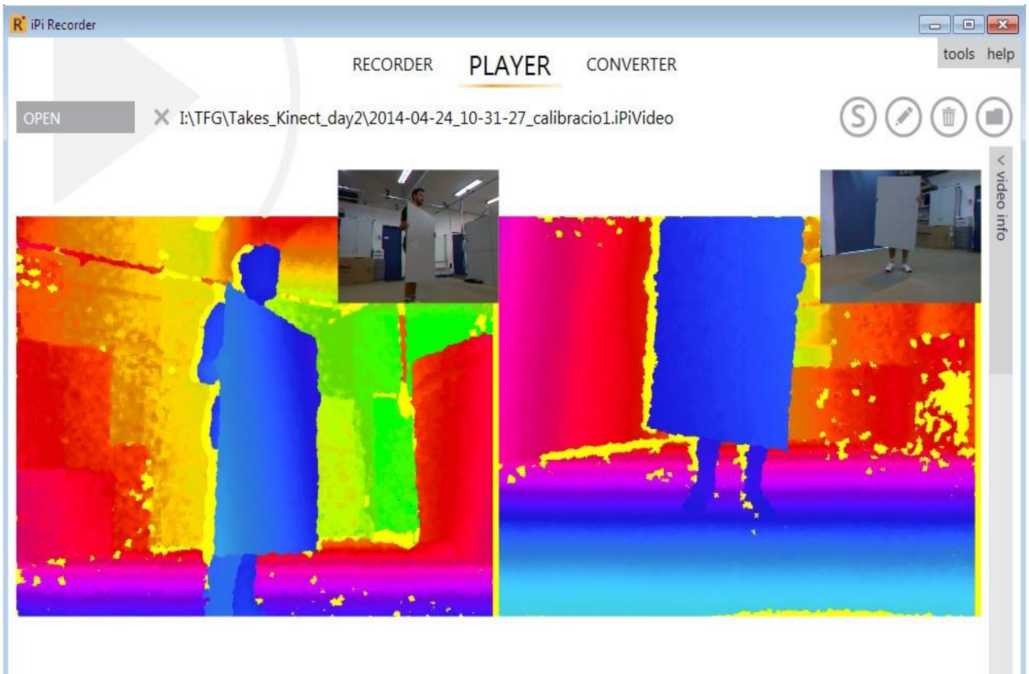


Figure 4.1.3. Calibration Recording

b) Motion Capture

Once the calibration was finished, the Kinect sensors were ready to capture motions. To record an actor's performance in iPi Recorder, it is necessary to follow a sequence. As soon as recorder starts, the actor begins with a "T-pose" position for several seconds and then starts the movements. The reason of beginning with a "T-pose" is for building the actor appearance model during tracking process. Subsequently, the video captured from iPi Recorder is processed in iPi Mocap Studio [13].

The first step to do in iPi Mocap Studio is to scale the model keeping the video in the "T-pose" position and adjust the height and length of the legs and arms. Once the model is adjusted roughly, by clicking on the button "Refit Pose", the software will automatically adjust the model on the actual subject. Given the adjusted model, the software is able to continue the process clicking on "Track Forward" button (*Figure 3.2.2.3*). Once the tracking process is finished, a refine process can be optionally run in order to improve the accuracy and correct minor tracking errors. After then, a post-processing filter called *Jitter Removal* will be applied so as to erase undesirable noise and preserve sharp, dynamic motions. Finally, a trajectory filtering will be applied to filter out minor noise that remains after *Jitter Removal* filter. As these last two post-processing filters are really powerful, the final skeleton animation was considerably assimilated to the original video.

After tracking the video, the next step is to analyse the data using iPi Biomech in order to obtain kinematic information. As the Kinect system captures the motion of the whole body, the data contains all the information. Consequently, to only extract information of the segments which will be analysed, in iPi Biomech section those elements that should be selected are Hip, Right Thigh, Right Shin, Right Foot, Left Thigh, Left Shin and Left Foot. As the relative angles of each joint will be compared with the marker-based system, only Euler angles has been selected and the coordinate system chosen is " Local (relative to parent joint)". Finally, all the selected data were exported in excel format so as to analyse with the other system afterwards.

4.2. Marker-based Systems

As the motions were captured using both systems at the same time, 34 markers were attached to the subject following the marker protocol in *figure 4.2.1*. Regarding the environment conditions of both systems, the subject (*Figure 4.2.2.*) moved in a limited space where both systems were able to capture the motions. The equipment of marker-based system was already installed in the Biomechanics Lab at ETSEIB. In this case, there was no need to make any calibration before capturing.

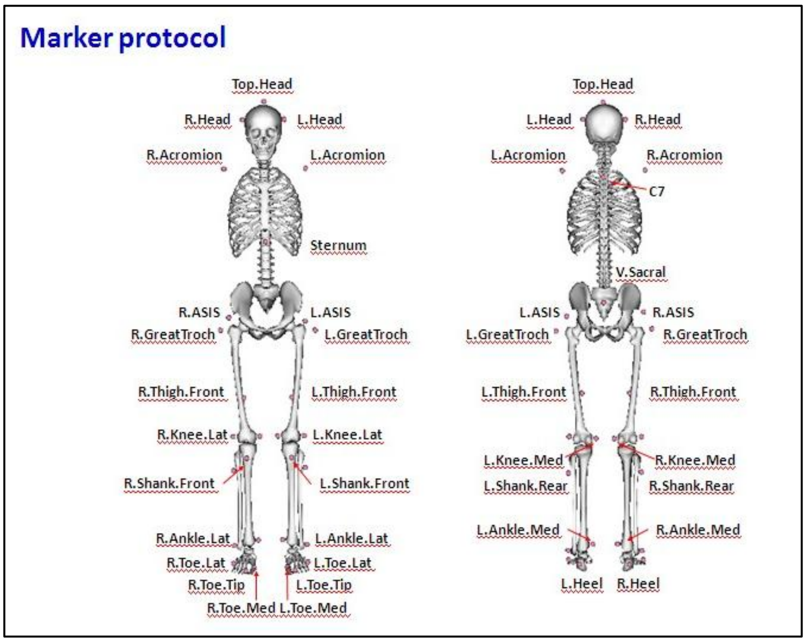


Figure 4.2.1. Marker Protocol

Figure 4.2.2. Actor with 34 markers attached on his body

For obtaining the kinematic data of the motions, it is necessary to follow three main stages which are the recording, the tracking and the data processing. After recording the movements using ARENA© [29], a file within the format of ".pt2" was generated. This file contains the position of the captured motion. Subsequently, ARENA is used to track the motion and obtain a ".pt3" file of trajectories. This file is converted into ".c3d" format so as to be read using a function in MATLAB [26]. Once a MATLAB file with ".mat" format was created, it was converted into a ".trc" format, which can be opened in OpenSim, by using a MATLAB program previously designed. While using OpenSim software, before analyzing the data, the first thing to do is to scale the model. Unless the errors obtained from the model are less than 2 cm, the model would not be acceptable. Finally, using the scaled skeleton model (*Figure 4.3.4.*), kinematic coordinates were obtained by applying "Inverse Kinematics" in OpenSim [28] and then a file with ".mot" format is generated. This format can be run in Excel or in MATLAB. The procedure of this methodology has been represented into a diagram which is shown in *figure 4.2.3*.

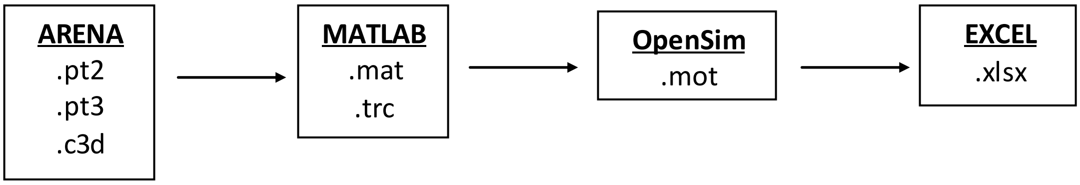


Figure 4.2.3. Diagram of the procedure to obtain kinematic data

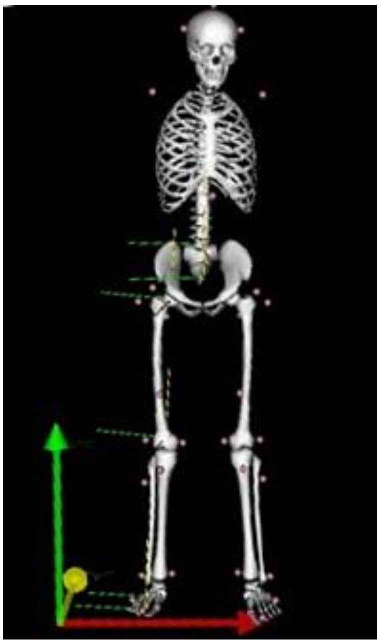


Figure 4.2.4. Skeleton model from OpenSim

5. RESULTS AND DISCUSSIONS

5.1. Data Post-processing

In the previous chapter, the methodology to capture motion using simultaneously two systems was explained. Both systems recorded the motion using different software and algorithms and as a consequence, the obtained data should be analysed independently. After that, the resulting information can be compared. In this chapter, the data post-processing procedure will be explained.

Marker-based systems provided kinematic results related to body joints, such as hip, knee and ankle, whereas marker-less systems provided kinematic results of each segment of the body as shown in *figure 5.1.1*. Moreover, the frequency to capture the images is different between maker-based system and Kinect system; the former one has a frequency of 100Hz and the latter one a frequency of 30Hz, that is to say, for each value obtained from Kinect system there are approximately 3 data from marker-based system. That is the main reason why the data obtained from the two systems can not be compared directly and should be post-processed in order to achieve the same frequency.

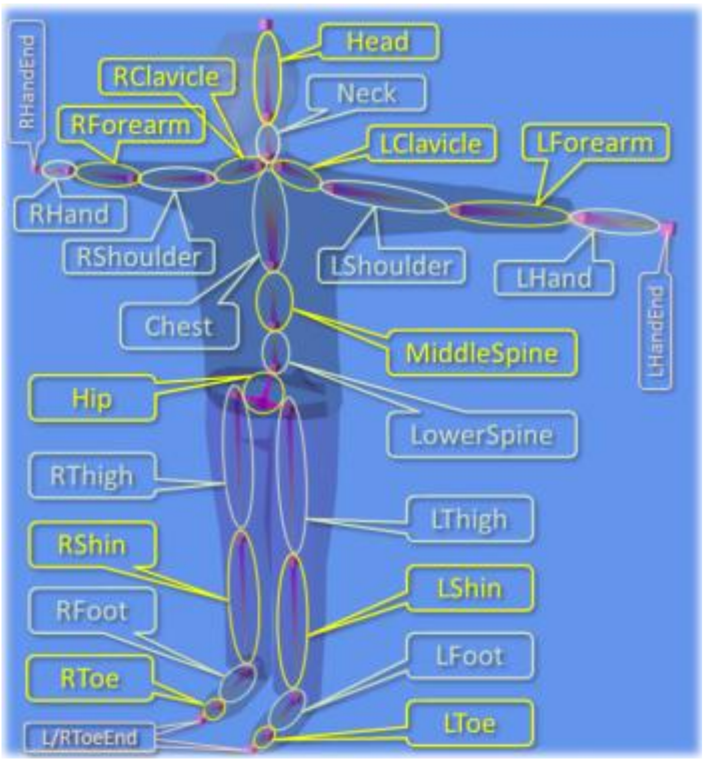


Figure 5.1.1 Segments of the body from Kinect software[2] [http://ipisoft.com/]

[2] In this figure the hip has been indicated as a segment, but it should be clarified that the hip is a joint.

Before comparing the results, it is important to extract the information which is necessary for this study. One of the problems to be solved, apart from the difference of the frequency, is to identify each articulation from marker-based system with the body segment from Kinect system. As it can be seen in the *table 5.1.1*, the data extracted from the excel file which was generated by the marker-based system are flexion and adduction of the hip, knee angle and ankle angle. On the other hand, the data extracted from the excel file of Kinect system are from the thigh, shin and foot. As the *table 5.1.2* shows, the iPi Biomech software provided the three rotation angles in X, Y and Z axes for each selected segment. The iPi Biomech gave more information data than OpenSim, so the first task was to identify which of the rotation angles that iPi Biomech provided correspond to one of the angle data from the marker-based system.

RIGHT	LEFT
hip_flexion_r	hip_flexion_l
hip_adduction_r	hip_adduction_l
knee_angle_r	knee_angle_l
ankle_angle_r	ankle_angle_l

Table 5.1.1. Data of joint articulation extracted from the marker-based system

RIGHT	LEFT
RX, RY,RZ of RThigh	RX, RY, RZ of LThigh
RX, RY, RZ of RShin	RX, RY, RZ of LShin
RX, RY, RZ of RFoot	RX, RY, RZ of LFoot

Table 5.1.2. Data of segment of the body extracted from the Kinect System

After making several graphics to compare the two systems, all the data from marker-based system have been identified with the Kinect system data. The rotation in X of the thigh segment in iPi Biomech matches with the hip flexion in OpenSim; the rotation in Z of the thigh segment matches with the hip adduction; the rotation in X of the shin segment corresponds to the knee angle and the rotation in X of the foot segment corresponds to the ankle angle. All is information is represented in *table 5.1.3*.

KINECT SYSTEM	MARKER-BASED SYSTEM
RX_RThigh	hip_flexion_r
RZ_RThigh	hip_adduction_r
RX_RShin	Knee_angle_r
RX_RFoot	ankle_angle_r
RX_LThigh	hip_flecion_l
RZ_LThigh	hip_adduction_l
RX_LShin	knee_angle_l
RX_LFoot	ankle_angle_l

Table 5.1.3. Identification of the data from Kinect with the data from Marker-based system

Once all the data were identified, the next task was to synchronize the frequency of both systems. As it is known, marker-based system has approximately 3,3 times more data than Kinect system. Consequently, all the values from Kinect should be kept and values from markers should be extracted in order to obtain the same number of values for two systems. For Kinect sensors, they take a frame per 0,0333 seconds while the OptiTrack cameras take a frame per 0,01. Knowing this, the third value of marker-based system is from the second 0,03 which is slightly earlier than 0,0333, for this reason, it is necessary an interpolation between the value of 0,03 and 0,04. Moreover, the 4th value of Kinect system coincides with the 11th value of marker-based system and this happens every 4 values of Kinect system. To facilitate this calculation process, a function of MATLAB was programmed in order to obtain synchronised data.

The interpolation equation is the following one:

$$x = x_1 + \frac{x_2 - x_1}{t_2 - t_1} \cdot (t - t_1) \qquad (Eq.\ 5.1.4)$$

where x is the unknown value between t_1 and t_2, x1 is the value in t_1, x_2 is the value in t_2 and the t is the time in seconds of the x value.

After identifying the data from both system and synchronizing the frequency of the data, now it is possible to compare the related joint angles in the same graphic. The results of the two takes will be shown in the following sections.

Once the results of each joint are compared in the same graphic, in order to determine the accuracy of the Kinect system, the Root-Mean-Square Error (RMSE) is calculated for each case (*Eq.5.1.5*). It measures the difference along time between values obtained with the marker-based system ($y_{M,t}$) and the values calculated by means of the Kinect system ($y_{K,t}$). The mean of the squared error is calculated over the total number of the values obtained which are also the number of frames of each take (N).

$$RMSE = \sqrt{\frac{\sum_{t=1}^{N}\left(y_{K,t}-y_{M,t}\right)^2}{N}} \qquad (Eq.\ 5.1.5)$$

Finally, the Normalized Root-Mean-Square Error (NRMSE) is calculated (*Eq. 5.1.6*), which is the RMSE divided by the range of marker-based system's values. This value is expressed as a percentage and it is used for comparing the accuracy taking into account the range of variation of the actual kinematic variable:

$$NRMSE\ (\%) = \frac{RMSE}{y_{M,Max}-y_{M,Min}} \cdot 100 \qquad (Eq.\ 5.1.6)$$

5.2. Results of Take 1

In each take, there are 8 graphics, 4 graphics of the right leg and the other 4 of the left leg. The 4 graphics represent the angles in degrees of hip flexion, hip adduction, and knee and ankle angles (flexion). In each graphic, the Y-axis represents the angle in degree and the X-axis represents the sequence of time in frames. In this first take, there are 488 frames which is equivalent to 16,27 seconds (frequency of the Kinect system). This movement consists of rising up and down both legs and walking slowly in circle.

The *table 5.2.1* shows the RMSE and NRMSE of each graphic. It can be observed that hip flexion angle and knee angle have a NRMSE less than 10% which is quite accurate. Nevertheless, the NRMSE of hip adduction angle and ankle angle are between 10% and 20% which is higher than before and rather significant.

Focusing on the figures of hip flexion and knee angle (*figure 5.2.1; figure 5.2.3; figure 5.2.5; figure 5.2.7*), the graphics suggest significant similarities between the Kinect and Marker-based system. Besides, *in figure 5.2.1*, a noticeable difference exists at the beginning of the graphic. The line of the markers remains stable at the value of -5º, whereas the line of Kinect points to an increase from -15º to -5º. The results indicate that the marker-based system has more oscillation, which means that it is quite accurate.

Nevertheless, the Kinect system seems to be smoother with little oscillation which indicates that the system did not catch the small variation of the joint rotation. The same happens to the hip flexion of the left leg, there is a significant variation about 10º at the beginning. (*Figure 5.2.5*)

Now, focusing on the figures of hip adduction and ankle angle, the graphics are consistent with the results of NRMSE. A considerable difference between Kinect and Marker-based systems can be observed. Especially, in the graphic of left ankle angle, it can be seen that there are no similarities of the curves obtained by the two systems. Note that although the NRMSE of right ankle angle is higher than left ankle (*Table 5.2.1*), the curves show the same tendency (*Figure 5.2.4*).The reason for this discrepancy is that there is a bias error between the two measurements, that is, the zero of the angle is not the same for both systems and should be better calibrated. Moreover, the curve of the Kinect in right hip adduction graphic seems to follow the general trajectory of the markers but with less oscillation.

	Hip Flexion Right	**Hip Adduction Right**	**Knee Angle Right**	**Ankle Angle Right**	**Hip Flexion Left**	**Hip Adduction Left**	**Knee Angle Left**	**Ankle Angle Left**
RMSE (º)	5,56	6,60	7,64	10,97	6,69	4,25	6,98	5,76
NRMSE (%)	7,64	19,14	8,24	20,90	8,70	18,16	6,29	13,89

Table 5.2.1 Results of RMSE and NRMSE

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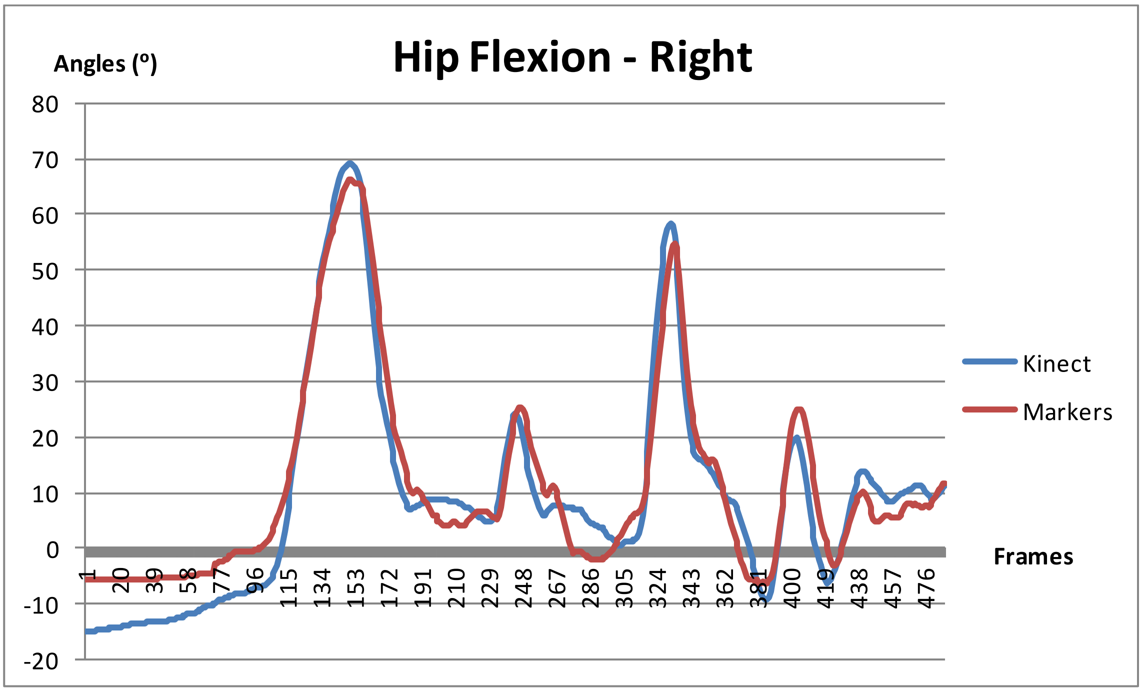

Figure 5.2.1.Angles of Right Hip Flexion (Take1)

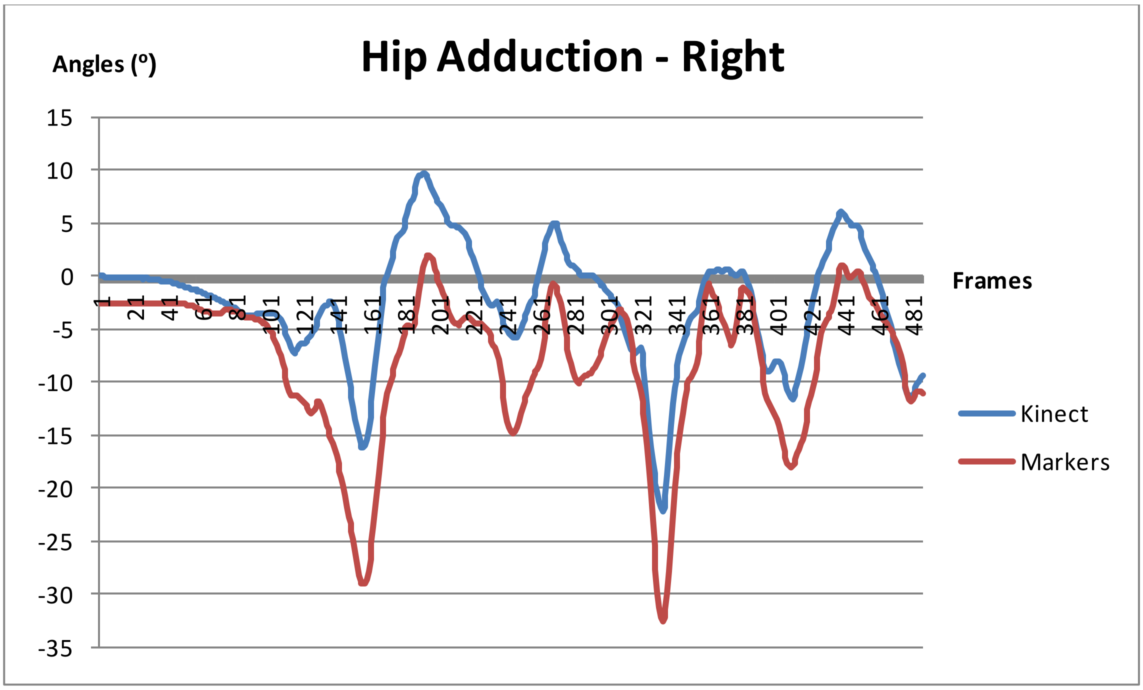

Figure 5.2.2.Angles of Right Hip Adduction (Take 1)

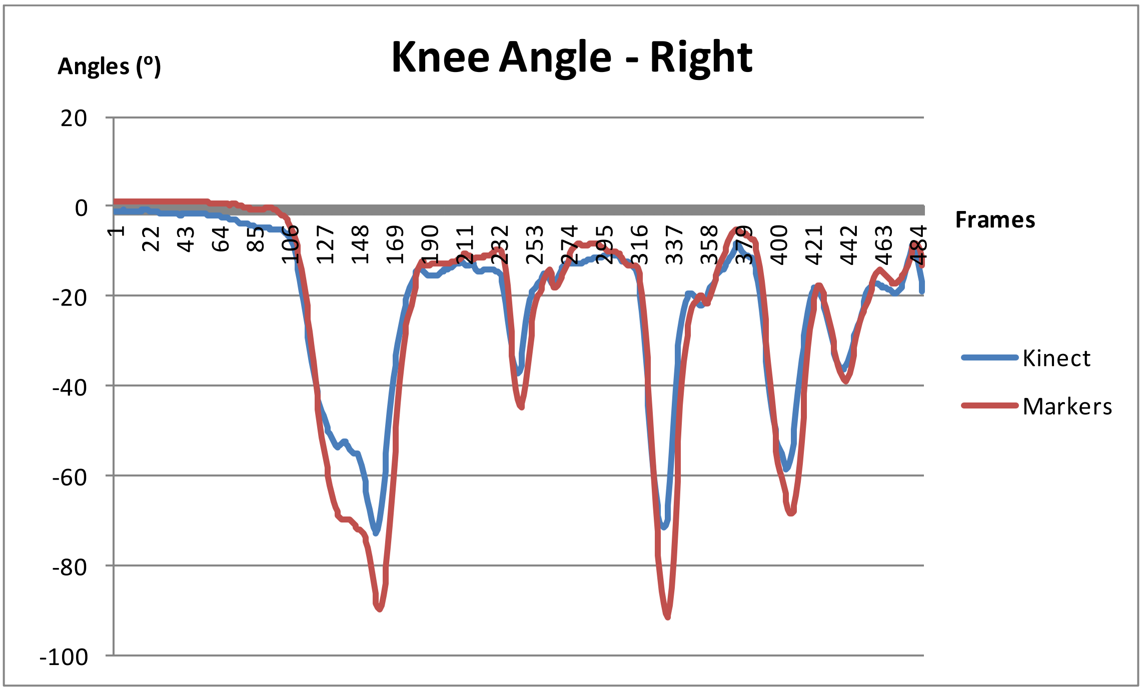

Figure 5.2.3.Angles of Right Knee (Take 1)

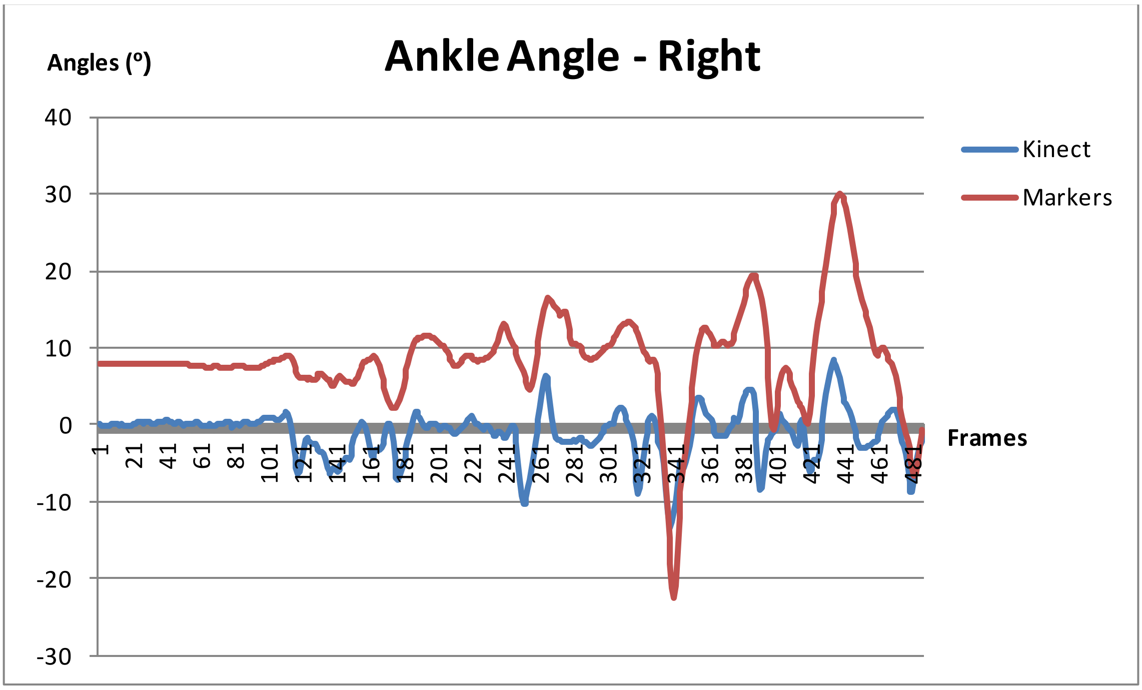

Figure 5.2.4.Angles of Right Ankle (Take 1)

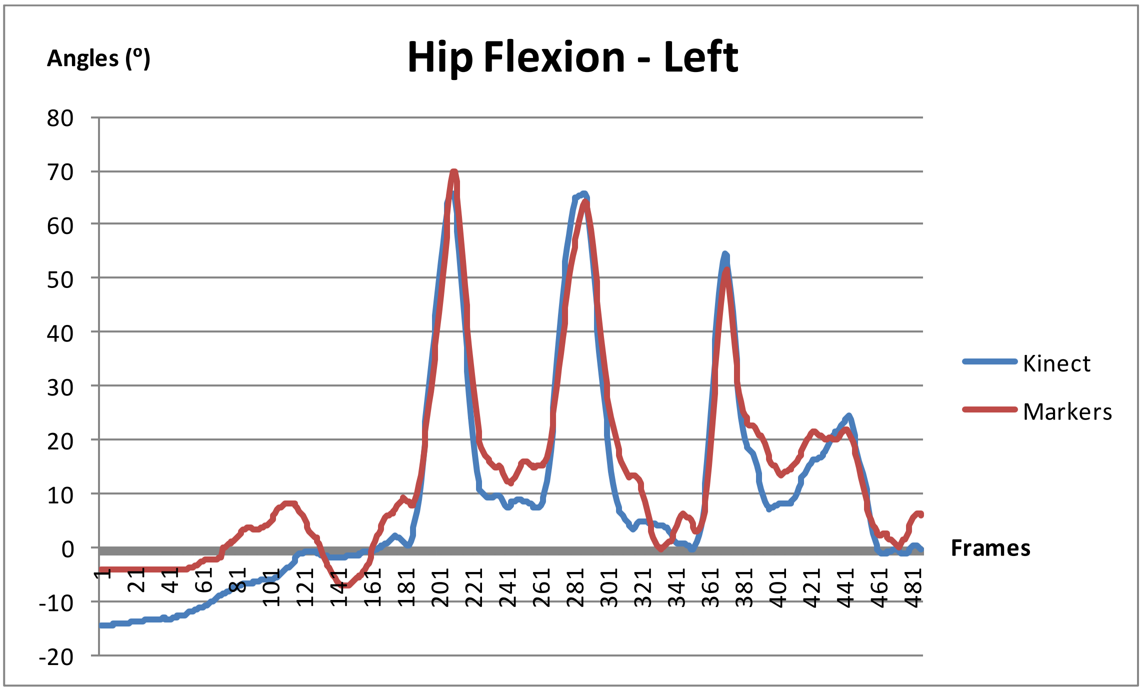

Figure 5.2.5.Angles of Left Hip Flexion (Take 1)

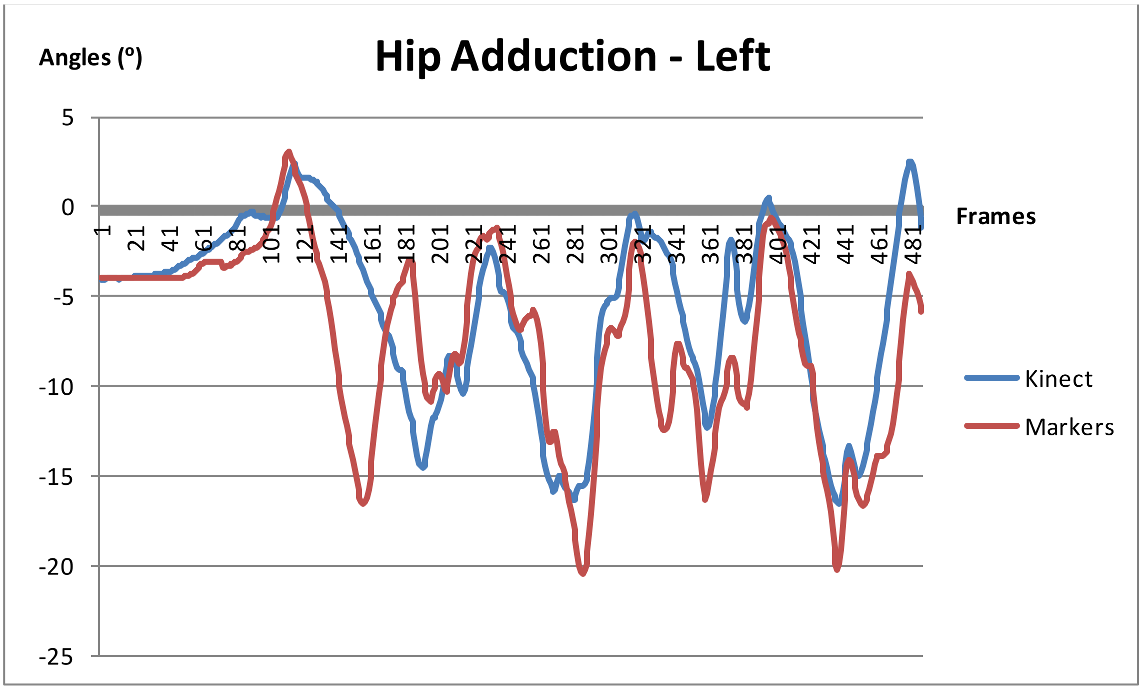

Figure 5.2.6.Angles of Left Hip Adduction (Take 1)

ETSEIB

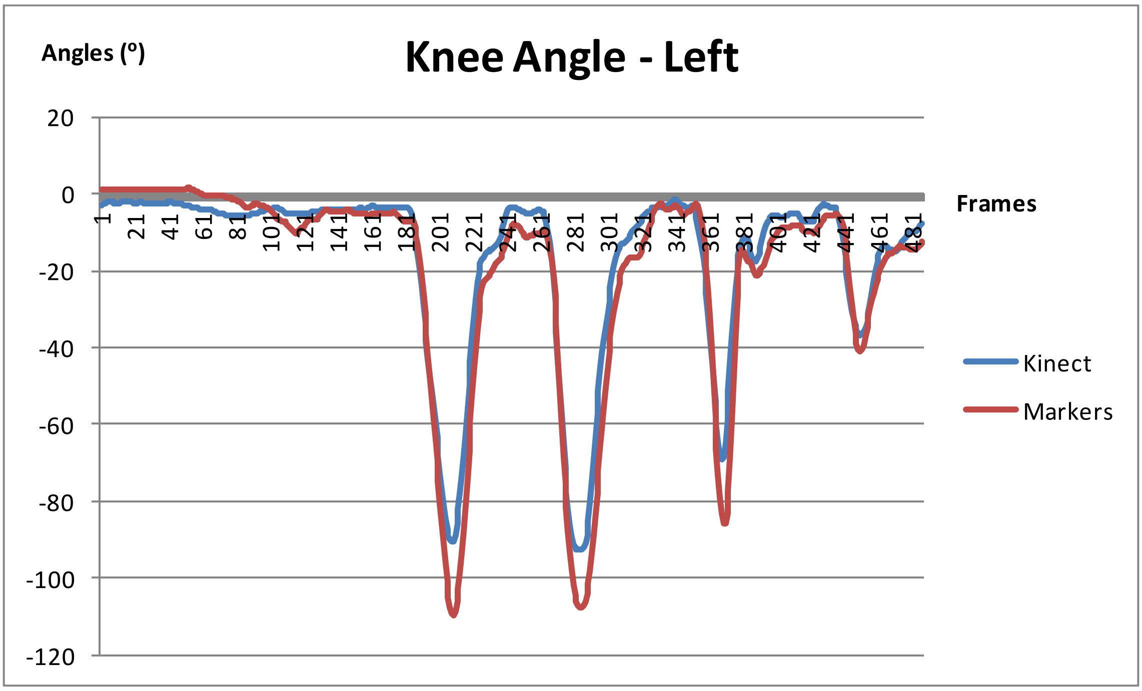

Figure 5.2.7.Angles of Left Knee (Take 1)

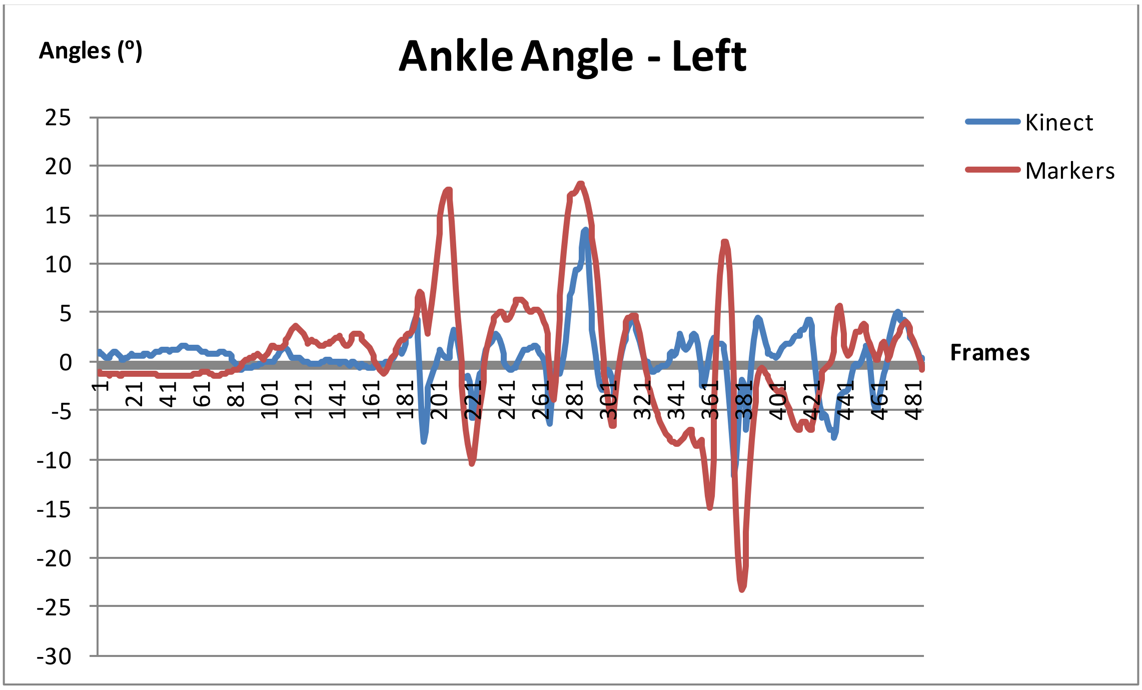

Figure 5.2.8.Angles of Left Ankle (Take 1)

5.3. Results of Take 2

In this second take, there are 485 frames which is equivalent to 16,17 seconds (Kinect frequency). The graphics represent the same as in the first take, where the Y-axis represents the angle (in degrees) and the X-axis represents the sequence of time in frames. This movement consists of walking in circle slightly more quickly than in the first take and squatting down once quickly. The movements of this take are relatively more rapid than the first one.

As in Take 1, here the *table 5.3.1* shows the RMSE and NRMSE of Take 2. It can be observed that hip flexion angle and knee angle have a NRMSE less than 10%, which agrees with the results in Take 1. However, the NRMSE of hip adduction angle and ankle angle are between 10% and 40%, especially the right hip adduction has the highest NRMSE of all. Comparing these results with the results from table 5.2.1, the NRMSE of hip flexion and knee angle have slightly decreased, whereas hip adduction and ankle angle are still having similar NRMSE than those in Take 1.

Focusing on the figures of hip flexion and Knee angle (*figure 5.3.1; figure 5.3.3; figure 5.3.5; figure 5.3.7*), it can be seen that the graphics obtained by means of the two systems are very similar. Moreover, in this take there is no considerable variation of the two systems at the beginning of the graphics. On the other hand, figures of hip adduction and ankle angle are not very similar. However, looking at the general form of the curve of Kinect, it follows the curve of Markers roughly within less precision. In the graphic of right hip adduction (*Figure 5.3.2*), between frames 321 and 341, the curve of Kinect reached its peak at 28º while the value obtained with the marker-based system is below 0. Because of this the RMSE of right hip adduction is the highest. Furthermore, the graphics of ankle angle of both legs indicate a poor assimilation to the curves obtained with the marker-based system.

	Hip Flexion Right	**Hip Adduction Right**	**Knee Angle Right**	**Ankle Angle Right**	**Hip Flexion Left**	**Hip Adduction Left**	**Knee Angle Left**	**Ankle Angle Left**
RMSE (º)	6,75	9,72	6,34	11,05	8,37	4,65	6,14	8,24
NRMSE (%)	6,48	36,65	5,28	19,74	8,58	17,12	5,20	14,02

Table 5.3.1 Results of RMSE and NRMSE

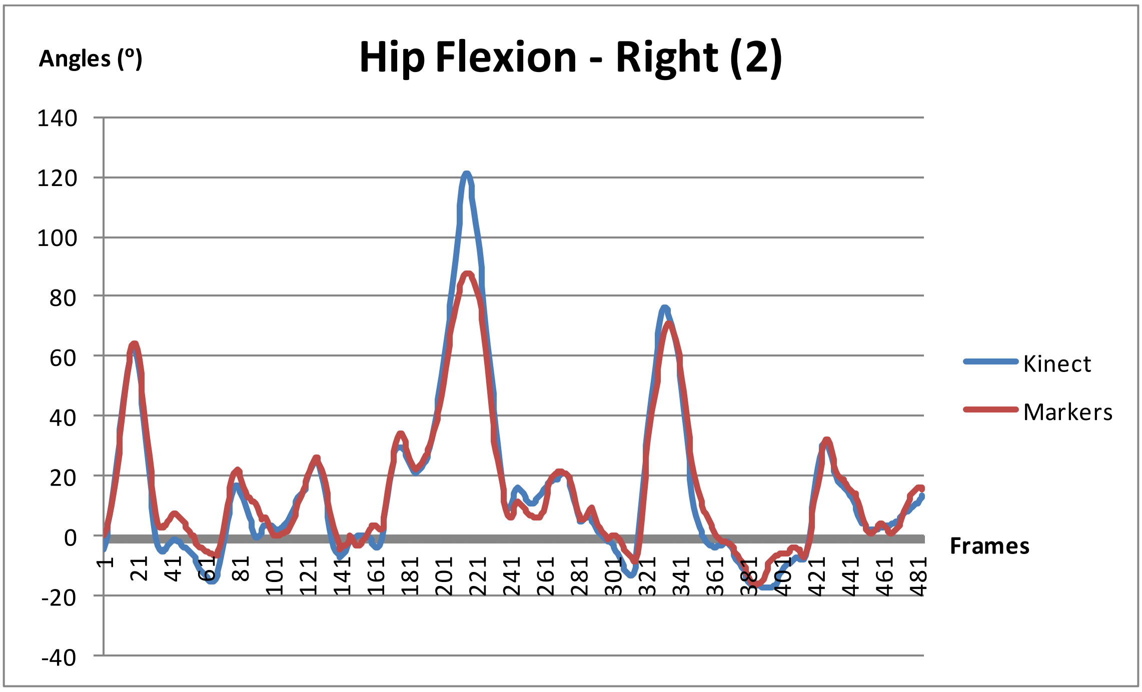

Figure 5.3.1.Angles of Right Hip Flexion (Take 2)

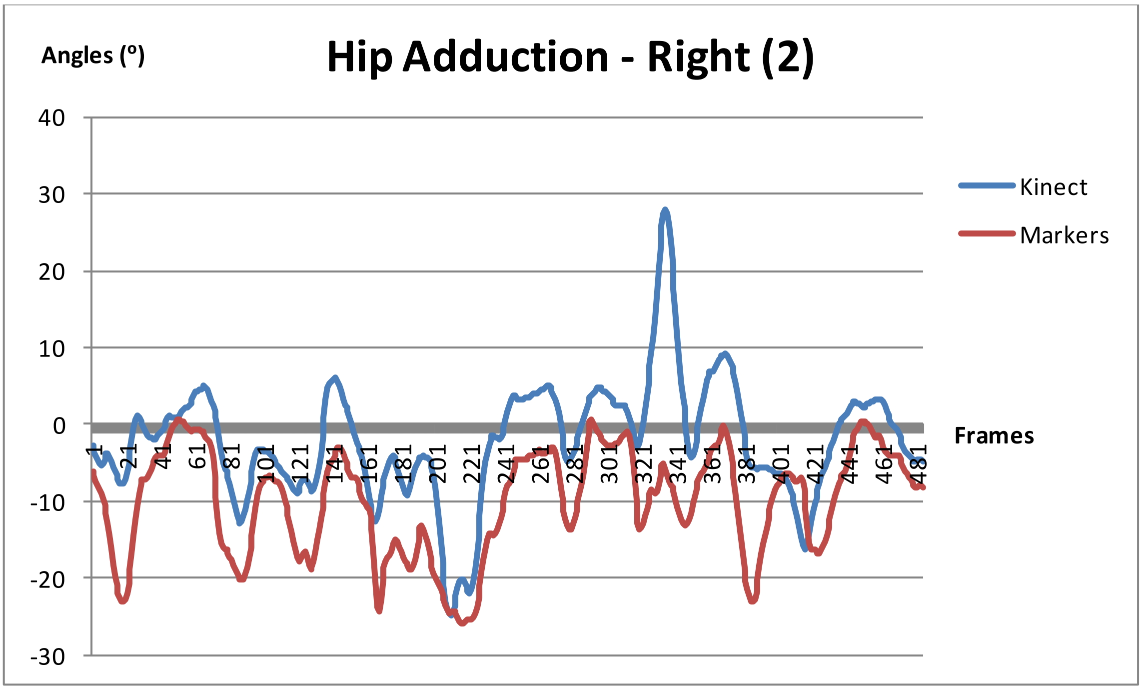

Figure 5.3.2.Angles of Right Hip Adduction (Take 2)

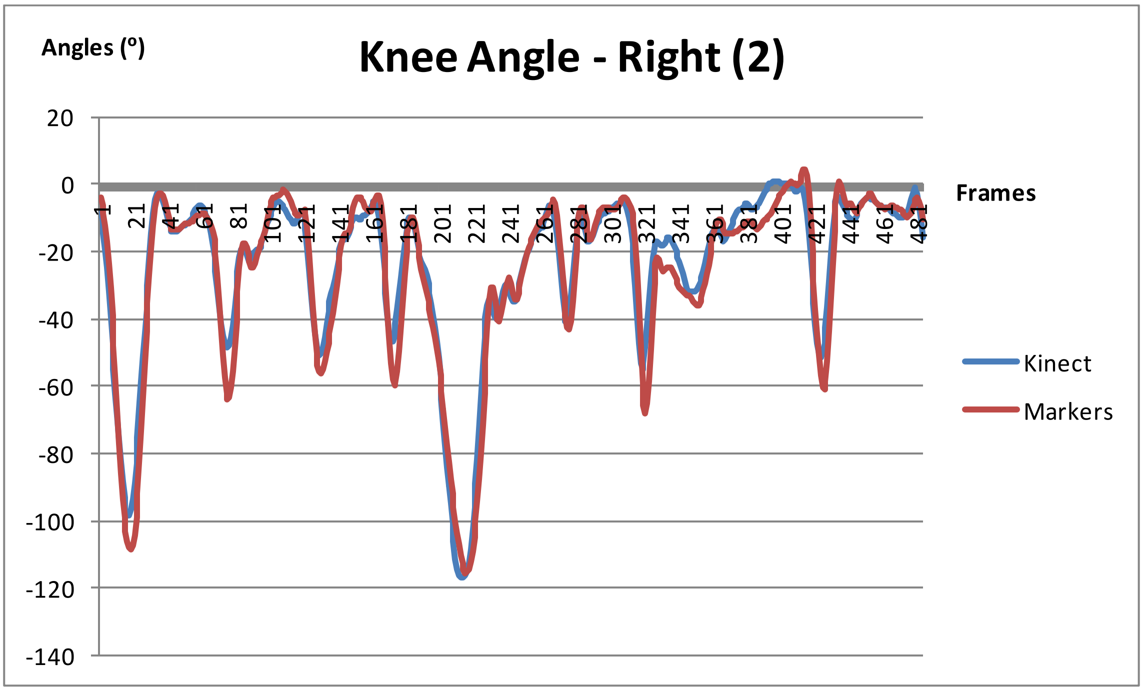

Figure 5.3.3.Angles of Right Knee (Take 2)

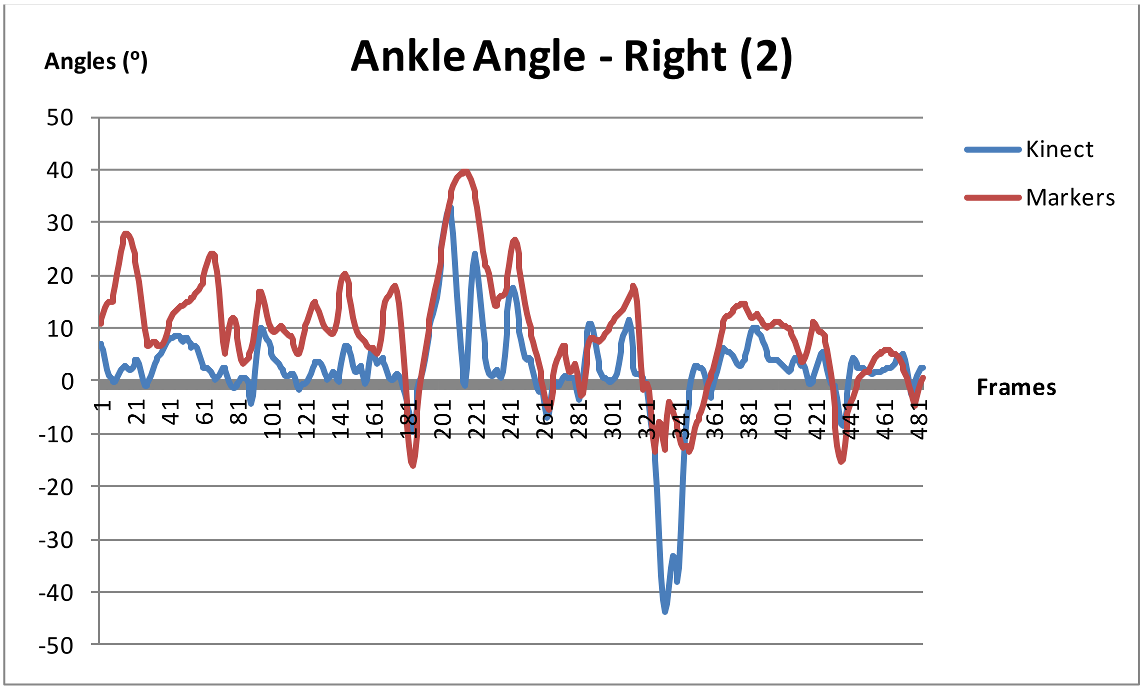

Figure 5.3.4.Angles of Right Ankle (Take 2)

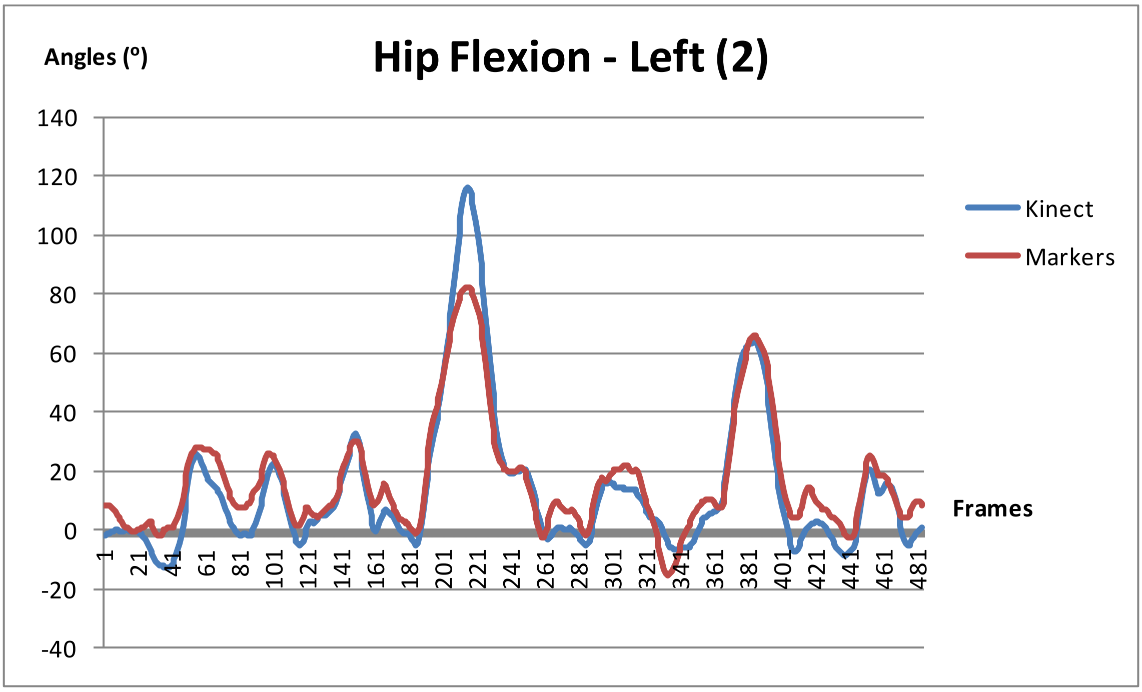

Figure 5.3.5.Angles of Left Hip Flexion (Take 2)

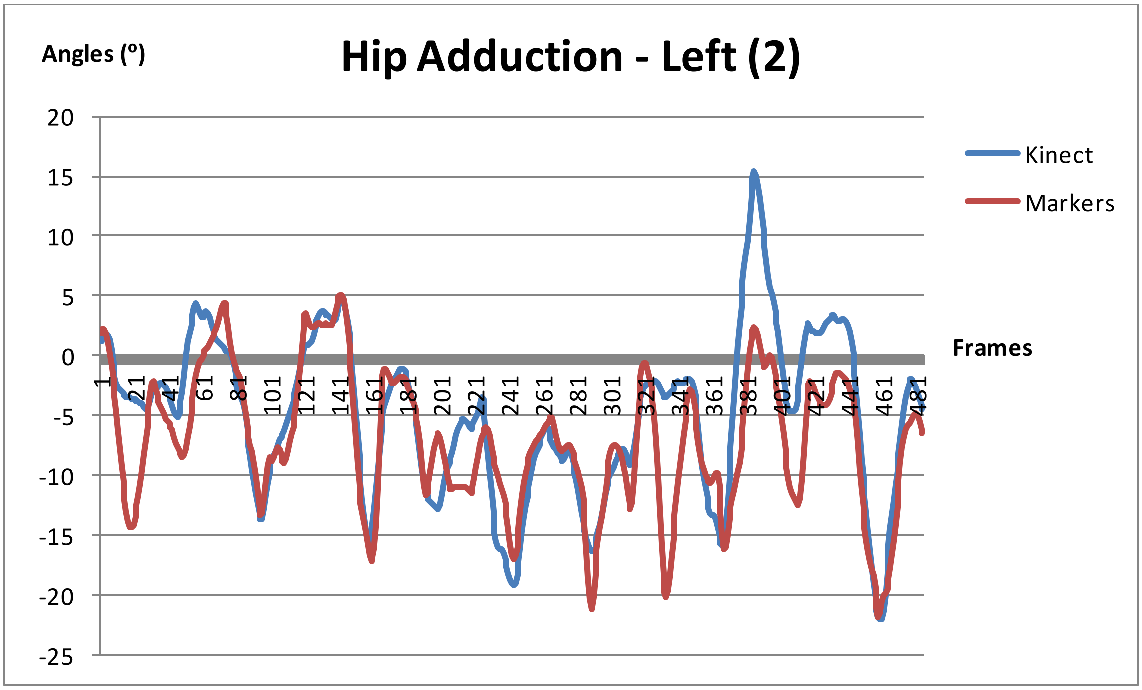

Figure 5.3.6.Angles of Left Hip Adduction (Take 2)

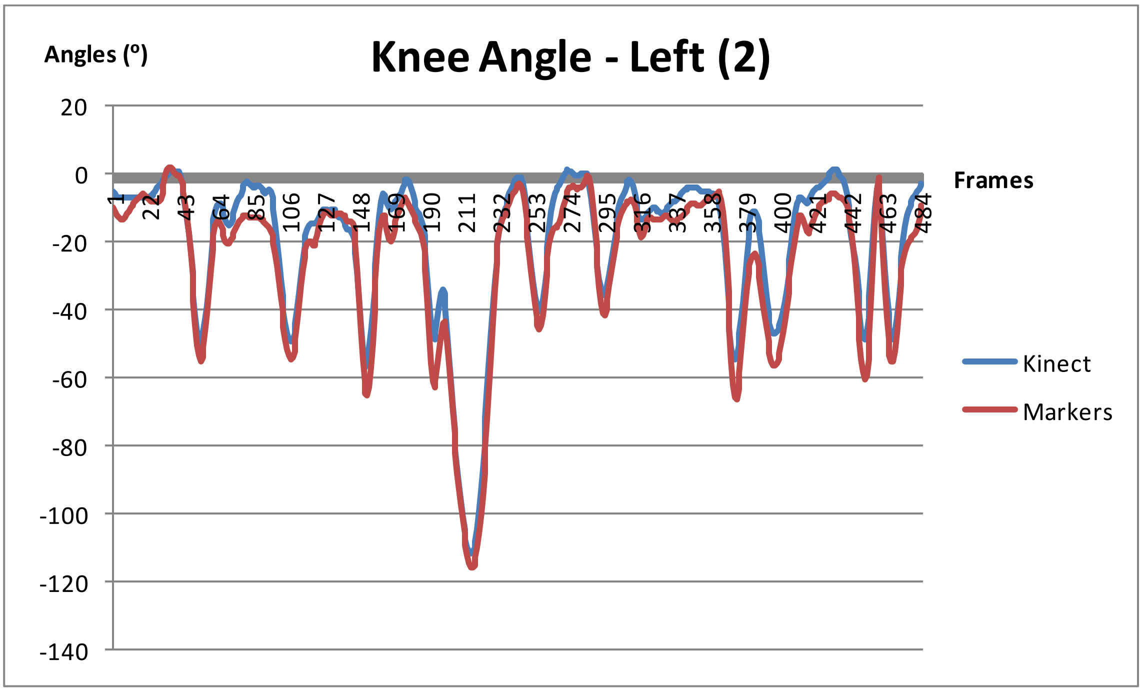

Figure 5.3.7.Angles of Left Knee (Take 2)

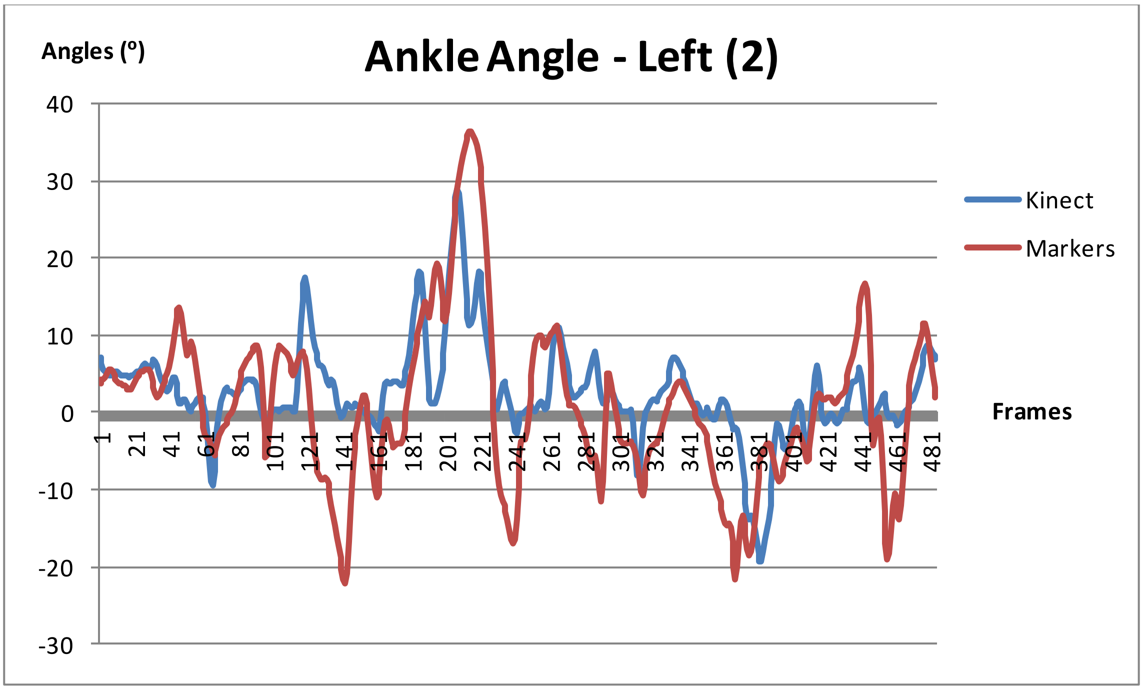

Figure 5.3.8.Angles of Left Ankle (Take 2)

5.4. Discussions

Regarding the results of Take 1, the hip flexion and knee angles obtained with the Kinect system match the best the curves calculated through the marker-based system. It is quite obvious that these two angles are easier to capture due to its wide range of movement. However, the angles of hip adduction and ankle are more difficult to detect due to its limited range of mobility. As it can be observed in the figures of Take 1, hip flexion and knee angles present a smooth shape where peaks can clearly be recognised, whereas the graphics of hip adduction and ankle angles present a lot of oscillations as in *figures 5.2.4* and *5.2.8*.

There exist two main causes of divergence between the results obtained by the two compared systems, problems, one is the bad motion tracking of hip adduction and ankle angles, and the other is the difference of angles at the beginning of the capture. The latter problem happens in the right and left hip flexion (*Figure 5.2.1; figure 5.2.5*), right hip adduction (*Figure 5.2.2*) and right ankle angle (*Figure 5.2.4*). After observing the skeleton animation together with the original video, it is concluded that several causes can yield the problems mentioned before. The possible causes are the following:

- Quick and sudden motion
- Inaccurate scaling of the model.
- Need for better post-processing.
- Occlusion (segments not visible by the cameras)
- Starting with a T-pose cause a variation of the initial position if the model is not well scaled.

Firstly, quick and sudden motions lead to an inaccurate tracking. It has been observed in the video that when the actor raised quickly the leg, the skeleton did not follow the movement as quickly as the actor but did it a bit slower. Secondly, the scaled model has not refined well the foot segments, it can be seen that the feet do not follow the exact movement of the actor and a better post-processing will be needed to clean up undesirable noises and tracking errors. Furthermore, occlusion can be one of the causes as well, it is probable that when the actor rotated, some segments would be hidden for some seconds and this will make difficult the tracking process. Finally, if the actor starts with a T-pose and the scaled model has not adjusted well at the beginning, there will be a variation of angles at the beginning of the video.

Now focusing on the Take 2, as in the Take 1, the hip flexion and knee angles have really acceptable results within lower NRMSE than in the first take. On the other hand, hip adduction and ankle angle present the same problems as in the first take. Especially the right hip adduction has the worst NRSME of all cases (*Table 5.3.1; Figure 5.3.2*). In this take, the actor performed more quickly than in the other take. It seems that moving quicker, generally does not affect the accuracy of the results. Actually, the NRMSE of the hip flexion and knee angle is slightly less than in the first take. After comparing the two videos, it is concluded that if the movement maintains the same velocity during the whole capture, it will be easy to track this motion using Kinect; yet making a sudden quick movement makes more difficult the tracking process. However, this problem can be solved applying correctly the post-processing filter unless the scaled model is accurate enough. Actually, the iPi Soft Mocap Studio is a powerful software, which can achieve better results by making the best use of it.

In brief, Kinect system is surely accurate to assimilate wide range of movements such as the angle of hip flexion and knee angles but not accurate enough for detecting small angles like hip adduction and ankle angles. In order to do accurate motion captures with the Kinect system, the studied motion should be performed smoothly and it is better when joints have a wide range of motion.

6. ECONOMIC CONSIDERATION

The cost of the project is calculated considering not only the fixed cost (€) of each item but also its life expectancy (years) and variable cost (€/h). Moreover, the cost should be calculated according to the time referred to project (h). For calculating the variable cost, the available working hours in a year has been considered 52 weeks, 5 days a week and 8 hours a day, except for the MATLAB licence which has been considered 52 weeks, 7 days a week and 24 hours a day. The hours devoted to this project are 300 hours (12 ECTS x 25h per ECTS). The hours spent in using each of the items are shown in *table 6.1.* The total cost of this project will be around 4.584,93€.

Cost Factor	Fixed cost expenses (€)	Life expectancy (years)	Variable cost expenses (€/h)	Time referred to project (h)	Cost of project (€)
2 Kinect Xbox 360	289,98	3	0,0465	10	0,465
Flat rectangular Board (from 50 x 70cm to 130 x150 cm)	17,96	1	0,0086	2	0,0172
Active USB 2.0 Cable (10m)	11,33	1	0,0054	10	0,054
Tripod	28,8	2	0,007	10	0,07
iPi Soft Motion Capture Basic Edition v2 + iPi Biomech Add-On	1.043,24	6	0,0836	90	7,524
Mocap System of Biomechanics Lab at ETSEIB	10.000	8	0,8012	90	72,108
Matlab License	500	1	0,0572	40	2,288
Supervisors	-	-	50	30	1.500
Student	-	-	10	300	3.000
Energy	-	-	0,008	300	2,40
	Total budget				**4.584,93**

Table 6.1 Calculation of the project cost

7. CONCLUSIONS

As it was said in the Introduction, the Kinect system is less accurate than the marker-based system. However, once finished the analysis and obtained the results, it has been verified that Kinect system is able to capture with enough accuracy the human motion with a reduction of time in the capture process. In the following paragraphs some conclusions will be drawn.

From the graphics obtained, it can be verified that, as expected, Kinect did not obtain exactly the same results as the marker-based system. However, by means of the data obtained from Kinect, it is observed that the system is able to provide a good approximation of the movement. Given the NRMSEs of each case, the most reliable results refer to the hip flexion and knee angles and the results of hip adduction and ankle angles are not accurate enough to be relied on. This suggests that Kinect is better for capturing the rotation pattern of the joints with a large range of motion.

Furthermore, the Kinect sensor has a lower sample frequency than the marker-based system. A direct consequence of this difference seems to be that the results obtained from Kinect are noisier than the marker-based system ones. This means that, despite both graphics are similar, the ones from the marker-based system capture better small and fast movements. Hence, the results suggest that the Kinect system responds reasonably well to slow movements that involve large joint ranges of motion. In addition, the lower frequency of the Kinect sensor together with the fact that measurements are noisier, involves having more uncertainties in joint angular velocities and acceleration, which may have an effect on inverse dynamics results.

In conclusion, Kinect system is a reliable system which permits to obtain acceptable kinematics results. Moreover, Kinect system saves significantly the time consuming process of attaching markers on the skin of the subject (which can take 15 to 20 minutes). In addition, the Kinect system is a new motion capture technology that is intended to be incorporated in the biomechanics Lab at ETSEIB in order to improve the equipment of the Lab. The most important consideration is that if Kinect is used in biomechanics studies, people should bear in mind that it provides general information of the movement but it is difficult to detect small variations. Nevertheless, it is believed that further research on this field will achieve to capture motion of whole body with accuracy.

8. BIBLIOGRAPHY

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