ABSTRACT

This project is aimed at developing a *Graphical User Interface* (*GUI*) for Gait Analysis, using the Matlab environment. The frequent captures performed on human walking, both on kinematics and ground reaction forces, in the UPC biomechanics Lab has brought to the necessity of developing a device in order to offer, to the user, a valid support for this kind of analysis.

We will start by treating the main matter, human walking, explaining its phases and the geometric spatial approach to analyze body motion. Later we will report examples of existing commercial platforms for Gait Analysis, outlining the main features of the device of interest, while in the third chapter a deeper explanation of the work's main characteristics will be reported, dealing with the body kinematic and dynamic components and describing the Lab equipment and configuration, the used software, the instruments and the GUI environment.

The fourth chapter contains all the theoretical basis used for the development of our project, explaining concepts like the used Anthropometric parameters or the filtering techniques, while the fifth chapter is a kind of guide for the GUI's utilization, with step by step description for each feature. Finally, we will report the conclusions and the achievements, providing also a list of future developments in order to improve the created device.

SUMMARY

PREFACE

This work, called “Development of a Graphical User Interface for Gait Analysis”, is about the final project for the Master of Biomedical Engineering. It has been developed concerning the Biomechanical area of the Department of Mechanical Engineering, at the “Escola Tècnica Superior d’Enginyeria Industrial de Barcelona” (ETSEIB).

The project is embedded with a LLP Erasmus agreement between the “Universitat Politècnica de Catalunya” and the “Politecnico di Torino”, leveraging the vast experience in the Gait Analysis field by the Department of Mechanical Engineering.

The developed work has benefited from collaboration with the “Universidad de La Coruña”, which has provided some of the routines we used and with which we began with the development of the interface.

Finally, the created GUI will be used in the UPC Biomechanics Lab of the ETSEIB, in order to perform the Gait Analysis with the support of this device.

INTRODUCTION

Biomechanics science consist on the application of Mechanics to biological world. Since mechanics is a mathematics' branch dealing with movement and its causes, the only difference between mechanics and biomechanics is about what is studied. Then, normally in biomechanics we are interested in the physiology underlying movement, like in muscles behaviour, nervous control or joints action and in the body's relations with external world, especially in terms of forces [Sellers, 2011].

The human body, in all its complexity, it is so seen like subject of the fundamental laws of mechanics, with relation to the biological systems' behaviours. The studying of biomechanics discipline is aimed to better understand muscles, joints and bones functions by applying musculoskeletal models, even for clinical purposes.

Particularly, the *Gait Analysis* is performed starting by kinematics capture and force plates' data, by the definition of anthropometric parameters for the observed subject and by the application of filtering techniques to the acquired signals. It is then possible to perform analysis like inverse dynamic or kinematical evaluations on the body modelled structure. The aims of this work are:

- The creation of a Graphical User Interface to assist the Gait Analysis, both in data processing and in post-processing;
- The development of different Anthropometric models, in order to be applied to the used human model, and the definition of filtering techniques;
- The creation of user-friendly interface that allows the visualization of the gait model video and the plotting of any kind of data, with the possibility to export them;
- To provide, finally, a useful device for directly performing Gait Analysis on the collected data.

CHAPTER 1

BIOMECHANICS OF HUMAN GAIT

In this first chapter we will treat some primal and useful matter in order to better understand the topics handled in our work. We will provide a description of the *Gait Cycle*, the main object of our study, in all its phases and events; then we will report information about the most conventionally used *Anatomical Planes* in Biomechanics and, finally, we will give details about the *Global* and *Local coordinate systems*, dealing with the international standards and the Lab conventions. We found also important to explain here the concept of *kinematical consistency* for biomechanical models, since we will not treat this matter in our project, even if of fundamental importance; it will be introduced for future developments of the work.

1.1 Gait Cycle

The *Human Gait* is characterized by two main features, necessary for any biped in order to make the act of walking possible: the first one is the *periodicity* of each foot in moving from one position of support to the next; the second one is the necessity of sufficiently rated *ground reaction forces*, exerted from the point of contact between foot and the ground, in order to support the body [Inman *et al*., 1981].

Like Vaughan *et al*. (1992) suggest, the human walking could be so considered like a cyclic act that recurs step after step; we can so narrow the description of the gait to a single cycle, with the large assumption that every cycle of the gait is the same (this approximation is not of general validity, but it is reasonable for the most of the population). In *Figure 1-1* there is an illustration of a single gait cycle; by convention, we assume that the cycle starts ussually when the tight foot makes contact with the ground [Vaughan *et al.*, 1992].

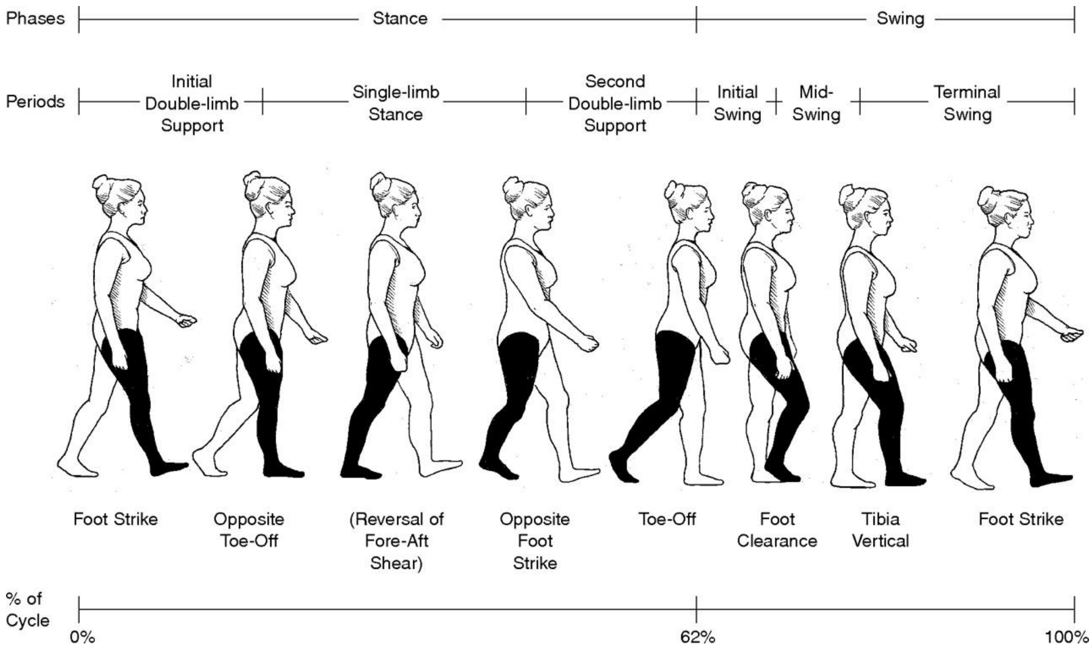

Figure 1-1. Gait cycle whit its phases and events (www.jaaos.org)

The walking cycle is normally characterized by two main *phases*: the *stance* phase, during which the foot is in contact with the ground, and the *swing* phase, in which the foot is floating, preparing for the next step.

The stance phase could be so divided in three other different phases:

1. *First double support*, in which both the feet are in contact with the ground;
2. *Single limb stance*, with the left foot floating and the right foot on the ground;
3. *Second double contact*, with both the feet again on the ground [Vaughan *et al.*, 1992].

The gait cycle is then divided into eights *events* (or *periods*), five during the stance phase and three in the swing phase. The names of the events are obtained from the foot movement (*Figure 1-1*). Traditionally, the events' names are:

1. *Heel strike*, that represents the start of the cycle, in which the body's centre of mass is in his lowest position;

2. *Foot-flat*, or rather the moment in which the surface of the foot touches the ground;

3. *Midstance*, in which the swinging foot passes the stance foot; it is the highest position for the body's centre of mass;

4. *Heel-off*, with the heel that loses contact with the ground and pushoff;

5. *Toe-off,* at the end of the stance phase; the foot is no more in contact with the ground;

6. *Acceleration*, occurring as the foot leaves the ground and the subject accelerates the leg forward;

7. *Midswing*, when the foot crosses the body in his lower part (midstance for the other foot);

8. *Deceleration*, referred to the action of the muscles, slowing the foot before the next heel strike [Vaughan *et al*., 1992].

1.2 Anatomical Planes

First of all, we need to define the *Anatomical position*, or rather the position assumed by a subject standing erect with the feet's plants in contact with the floor, the arms at the sides and palms, face and eyes standing forward. This kind of definition is necessary in order to provide a standard position of reference for anatomical descriptions [Saladin, 2004].

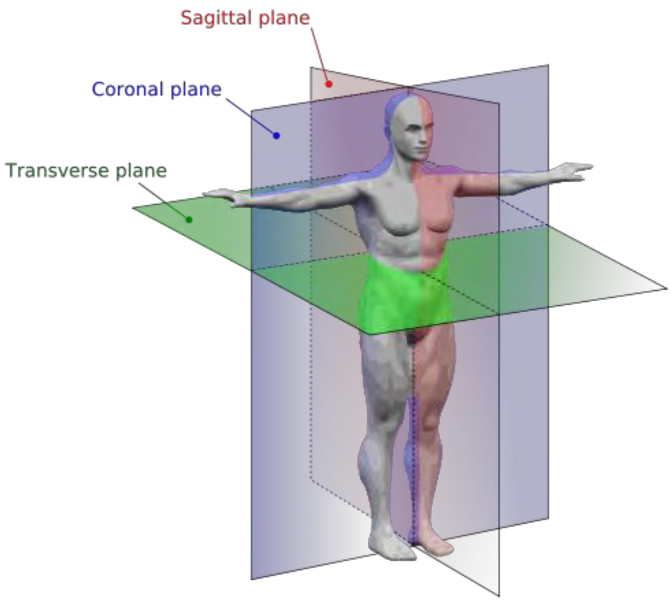

Figure 1-2. Anatomical Planes (www.mananatomy.com)

Many anatomical views are considered starting by specific sections, called *Anatomical Planes*, passing through the body. The three main anatomical planes, with reference to the *Figure 1-2*, are:

- *Sagittal* plane, passing vertically through the body, dividing it in left and right sides: this is so also called *median* or *midsagittal* plane;
- *Frontal* or *Coronal* plane, passing vertically and perpendicular to the sagittal plane; it divides the body in frontal and back parts;
- *Transverse* or *Horizontal* plane, crossing perpendicularly the body's long axis and dividing it in upper and lower parts [Saladin, 2004].

1.3 *Segment Coordinate System* (*SCS*) and Global reference system

In this section we will report the global and local reference frame provided in the Segment Coordinate System (SCS) and defined by the *Standardization and Terminology Committee* (*STC*) of the *International Society of Biomechanics* (*ISB*) for the total body and for each segment, comparing it with the Global and the Local reference systems used for the Lab data capture and adopted in our work. It is important to notice how all the equations and the parameters used in this work [from Vaughan *et al.*, 1992, Ambrosio & Kecskeméthy, 2007, Dumas *et al.*, 2007] are referred to the SCS, so it has been necessary to execute a change in coordinate systems in order to refer all the dimensions to our local and global systems.

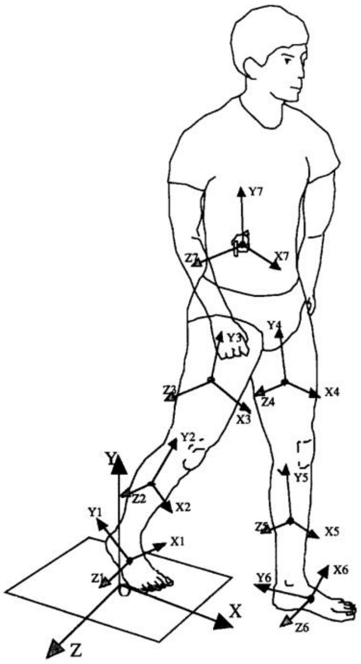

Figure 1-3. ***Global reference frame*** **and** ***segmental local centre of mass reference frame*** **as defined by the STC [Wu & Cavanagh, 1995]**

We will report, as it follows, the definition for *Global reference frame* and *segmental local centre of mass reference frame*, or rather the respectively the global and the local coordinate systems as defined in the SCS (*Figure 1-3*):

- The Global Reference Frame is a reference system in which the direction of the global axis are consistent, independently from what kind of movement is performed by the subject. Typically, for its definition we use the notation X, Y and Z, with the axis triad defined as a right-handed orthogonal triad fixed in the ground, with the positive Y axis upward with direction parallel with the field of gravity, while X and Z are in a plane perpendicular to the defined Y axis, with the Z axis exerted from the sagittal plane and directed towards the right side with respect to the walking;

- The *segmental local centre of mass reference frame* is obtained in order to provide a coherent definition of each ith segment position and orientation. It is so expressed by the notation X_i, Y_i and Z_i, with each ith orthogonal triad fixed to the segment centre of mass, with the positive X_i axis anterior, the positive Y_i axis directed towards the proximal joint and Z_i defined by a right-hand rule [Wu & Cavanagh., 1995].

In our work we used different coordinate systems, following the standard adopted by the used capture cameras. The Global and the Local are so defined as it follows:

- The *Global* reference system with the axis triad defined as a right-handed orthogonal triad fixed in the ground, with the positive Z axis upward with direction parallel with the field of gravity, while X and Y are in a plane perpendicular to the defined Y axis;

- The *Local* systems, positioned all in the centres of mass of each segment, have all the same configuration of the Global system in the anatomical configuration of the body.Then, they move attached to the segments. The X axis is so defined, both for the Global and the Local systems, in the gait direction.

1.4 Kinematical ***consistency***

A mechanical system is considered *kinematically consistent* if all the related constraint equations and the corresponding time derivatives are satisfied. In inverse dynamics, for example, we can obtain spurious reaction forces from violations of constraint equations, in case of non-consistent system.

The process of kinematic data acquisition naturally brings to errors in the evaluations of the distances between anatomical points, producing non-consistent structures of the considered biomechanical model due to violations in kinematic constraints. This kind of error is typically impossible to eliminate, being due to limited resolution of video image, operator errors in digitizing, skin movement or to the approximation of the anatomical joints with specific mechanical joints.

In order to ensure the kinematic consistency it is needed to operate on the Cartesian coordinates in way that the distances between anatomical points is constant during the analysis, obtaining a new set of point position, consistent with the kinematic structure of the model. This could be made with different approaches, for example by calculating mean averaged length for the points distance starting by the first points' non-consistent positions and by imposing these lengths to the kinematic structure during the analysis; another way to impose consistency is that of directly provide the effective measured anthropometric dimensions of the observed subject [Silva & Ambrosio, 2002].

CHAPTER 2

STATE OF THE ART

This chapter gives to the reader a brief general idea about the existing platforms in the *Gait Analysis* field. Since our work is aimed to the development of a *GUI*[1] for Gait Analysis, it is important to understand what normally a user is expected to be provided in an interface for this kind of investigation, looking around to the developed software.

In what follows we will provide some examples of existing software, analyzing their interfaces. Particularly, we will deal with the platforms developed by *Biogesta*, *VISOL*, *Motion Anlysis*, *OpenSimulator*, *LifeModeler*, *AnyBody* and *PhoeniX Technologies Inc.*. The aim of this chapter is finally not that of defining a starting point in order to improve the existing platforms by making a final comparison, but that of exploring the main features of a Graphical Interface for Gait Analysis by the definition of the functionalities that our GUI must provide, the available data and the offer of an user-friendly interface.

2.1 *Biogesta* platform

Biogesta is a French society specialized in software development for movement analysis. Particularly, we are interested in their product named *SAGA-3*^{RT}, a software made to manage till 255 cameras, connected to a Ethernet system. A calibration frame is no needed and the 3D reconstruction is normally automatically done. This kind of software is also able to take

[1] *Graphical User Interface*, we will provide a description in the next chapters

signals from the external acquisition system, like force platforms or EMG. Even Bluetooth transmission is possible.

Several functionalities are available, both in processing and analyzing data, like filtering, graphs displaying and animation. All the acquired data can be exported in different format files, like *.txt* or *.avi*. In the picture that follows (*Figure 2-1*), an example of interface by Biogesta's software is shown [Biogesta, 2000].

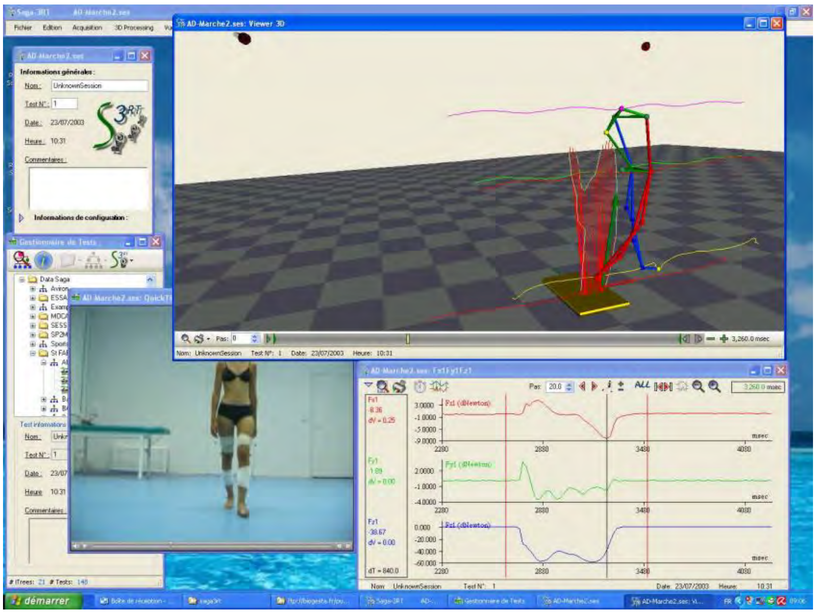

Figure 2-1. Display example for *SAGA-3*^{RT} software – *Biogesta* (www.biogesta.fr)

2.2 *VISOL* platform

VISOL is a Korean brand that develops 3D Motion Analysis software, like *Kwon3D*. This software provides a rigid body model, manual digitization and automatic tracking of the markers and processing features like Butterworth low-pass filtering. It is possible to analyze the collected data and extrapolate points and Centres of Mass kinematics, to obtain orientation matrices to transform the local reference frames, body orientation angles and angular kinematics and to operate Inverse Dynamics[2]. Finally, the interface allows the visualization of 3D animation, Graphs and Data views (*Figure 2-2*) [Visol].

[2] We will treat this topic in the next chapter (3.2)

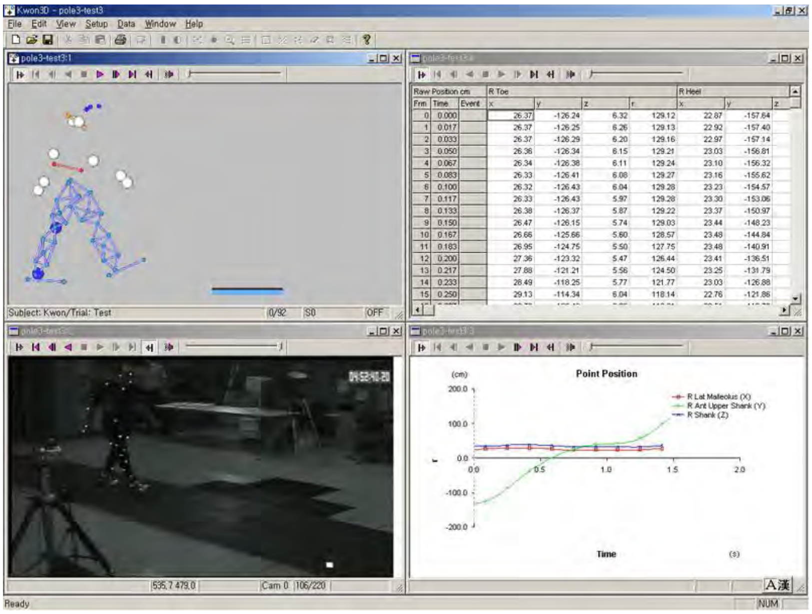

Figure 2- 2. *Kwon3D* product's interface, by *VISOL* (www.kwon3d.com)

2.3 *Motion Analysis* platform

Motion Analysis, a high performance optical instrumentation systems producer brand, provides the *SIMM* software; SIMM (Software for Interactive Muskuloskeletal Modelling) is a device for modelling, animating and analyze 3D musculoskeletal systems, recurring to model made by representing components like bones, muscles and segmental links. This tool enables the analysis of the musculoskeletal model, allowing the user to interact with this, by changing its geometry and other model parameters related with muscles during the simulation and exploring the produced effects. Finally, SIMM allows the simulation of human actions like walking, in which we are interested.

The model created by SIMM is made by segments connected by joints; these latter are modelled with reference to accurate kinematic equations. The model also contains muscle-tendon actuators, developing forces and creating moments about the joints.

SIMM provides a lower plus upper body model, so that it is possible to make biomechanical evaluations, like gait analysis by using the lower model, monitoring parameters like velocities, moment arms, accelerations or forces on the joints during normal and pathologic gait; the complete visualization of the relation between the body and the external forces and of the total body motion is allowed [MotionAnalysis, 2011].

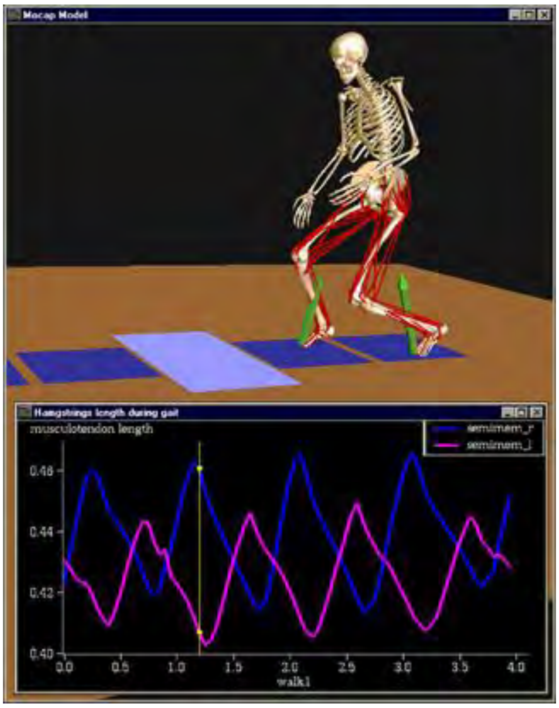

Figure 2-3. Simulation frame by SIMM platform (www.motionanalysis.com)

2.4 *OpenSimulator* platform

OpenSim is an open-source product by the *OpenSimulator* core developers of Simtk.org; it provides a platform for modelling, simulating, and analyzing the neuromusculoskeletal system and it is based on data, models and computational tools related to physics-based simulation of biological structures. The software's routine are developed in ANSI C++ environment, so that, in order to add a tool, a user must write a new C++ code; the graphical user interface is made in Java.

The user can simulate the human movement by firstly creating a dynamic model of the musculoskeletal system, with its relations with the external environment. In order to do this, the user must set equations describing muscles' contractions and geometry and the body segments' dynamics (*Figure 2-4*).

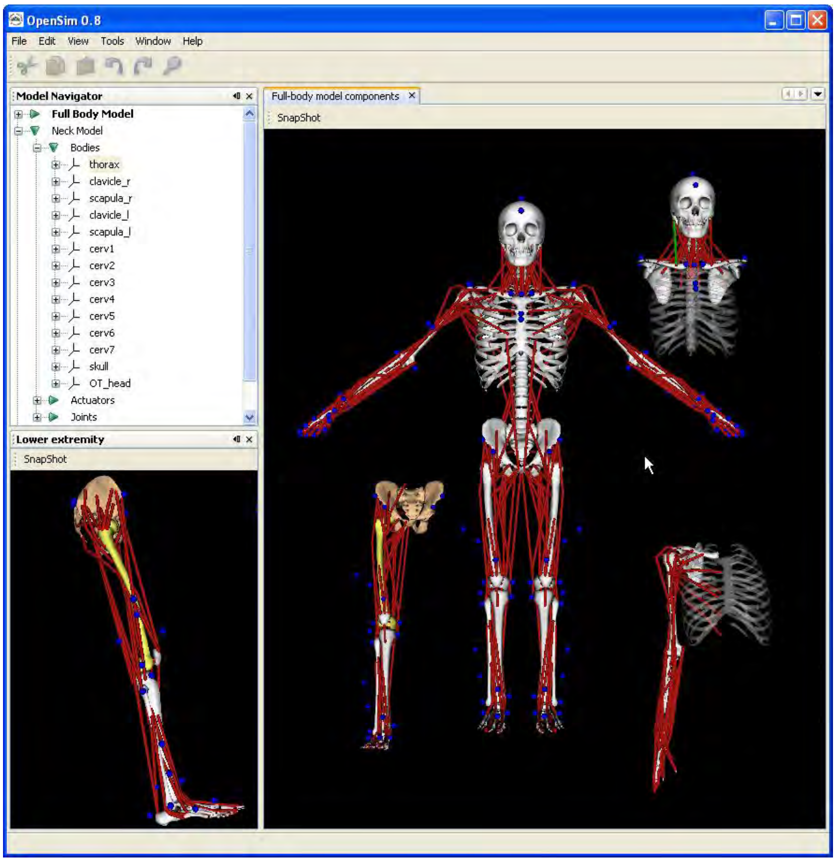

Figure 2-4. Screenshot from OpenSim, showing models of different musculoskeletal structures [Delp *et al.*, 2007].

The *SimTrack* tool provides a guide for the user that, in four steps, can create a dynamic simulation; this device starts by taking as inputs the musculoskeletal created model and external data, like measured kinematics and reaction forces and moments [Delp *et al.*, 2007].

2.5 *LifeModeler* platform

LifeModeler, a human simulation software developer company, created the *LifeMOD* platform for human movement analysis; this device allows the user to develop a human model defining values for few subject parameters, like age, height, weight and gender; starting by an anthropometric database, the software creates automatically the structure, or rather the model's bones, muscles and joints and it lets also the user to define the external environment in which the simulation will take place.

The human gait can be performed using 3D motion-capture data, imported into LifeMOD that provides the motion, allowing simulations like inverse and forward dynamics. Standard plots of parameters like forces, torques, displacements, velocities, accelerations, angles are automatically produced [LifeModeler, 2009].

2.6 *AnyBody* platform

The *AnyBody Technology A/S* brand presents the *AnyBody Modeling System*™ device, a software that simulates the human body system mechanical working, in relation with the external environment. The latter is defined by the exerted forces and the boundary conditions, with the user that can also set the subject posture or the kind of motion.

The software makes available results like muscle and joints forces and torques, elastic energy in tendons, muscle action and allows the scaling of the human body model in relation with the anthropometric data, defining every kind of population or individual. The software's created model can also be moved by Motion capture data imported from external systems. An example of the software's display is reported in the *Figure 2-5* [AnyBody Technology].

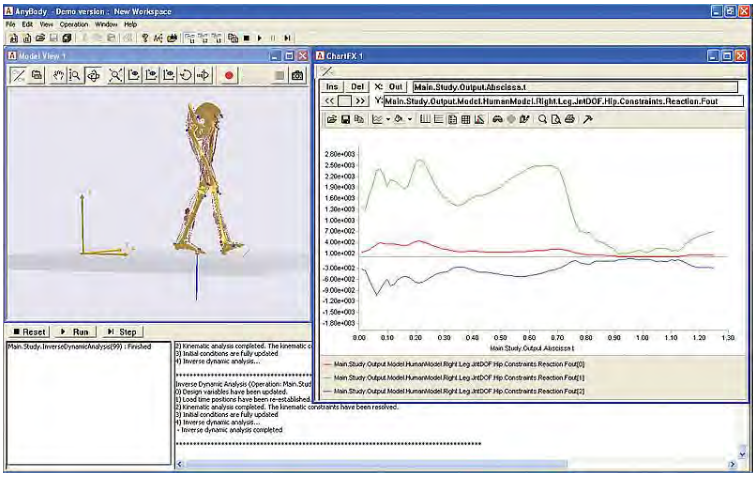

Figure 2-5. ***AnyBody Modeling System*™ display for gait analysis (www.anybodytech.com)**

2.7 *PhoeniX Technologies Inc.* platform

The Canadian *PhoeniX Technologies Inc.* Company provides the *VZSoft*™ graphical interface which allows the user to arbitrarily set up the order of markers sampling, removing the necessity of ordered placement of the markers preceding to the capture. Particularly, a very user friendly display is provided to the user, with a very intuitive terminology and with the most of the functions performed automatically: the user has so to select just few parameters, using the software and its applications without knowing the technology at the basis of working [PhoeniX technologies Incorporated, 2007].

CHAPTER 3

METHODS

In this chapter we will provide all the techniques, the methods and the theoretical basis used in the development of our project or related with his results; we will start by defining the *Kinematics* of the human gait, referring to the body's joints and segments, and then we will study the *Dynamics* of the movement. In the following sections a description of the Lab, the motion capture systems and software used will take place, with a part orientated to the markers system. Finally, we provide a description of the *Graphical User Interface* (*GUI*) tool from Matlab and of the used *c3d server* for motion analysis.

3.1 Kinematics of Human Gait

With the term *Kinematics* we refer to the definition of the motion, independently of the forces that cause it. We consider as Kinematics dimensions like linear and angular displacements, velocities, accelerations and joint angles. We can collect this kind of information by using direct methods (i.e. goniometers, accelerometers) or indirect methods, using imaging techniques (i.e. cinematography, high-speed video, stroboscopy) [Rodgers, 1988].

In order to study the human kinematics, we must consider the total body like a block of rigid bodies, the *Segments*, kept together, in their points of conjunction, by *Joints*: we consider, so, separately the treatment of the movement kinematic for these two kind of elements (*Figure 3-1*).

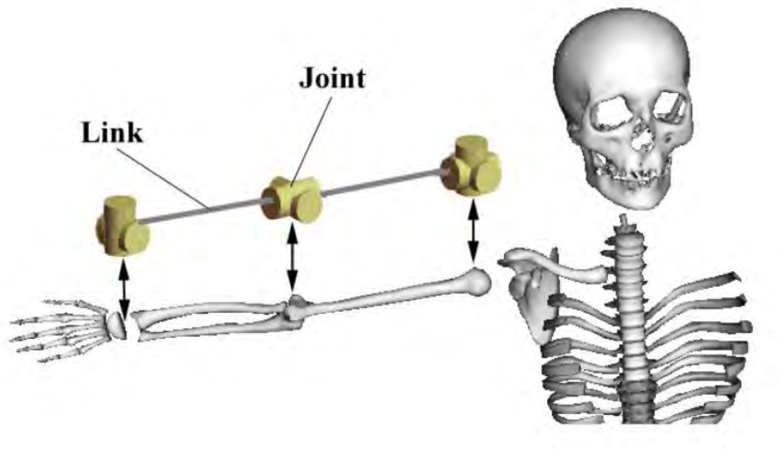

Figure 3-1. Skeleton model with Joints and Links (Segments) [Farrell, 2005].

3.1.1 Kinematics of Anatomical Segment

First of all, we need to define the meaning of *Centre of Mass* (*CM*) for each segment like the only location for the considered system, changing in time, that is the result of the average position of the system's mass [Patrap & Ruina, 2001].

Considering a *reference frame* like a coordinate system defined by an *origin* and a *base* (axis triad), as reported in the first chapter (1.3) we can differentiate between *global* and *local* reference frame: the first one has his origin in a reference point fixed on the floor (typically reported like O) and his base is made by the *XYZ* axis; the local reference frame has indeed the origin corresponding with each segment's CM and the base, $x_i y_i z_i$, fixed to the limb: the local reference system can, so, change its position along time, moving in the space when the segment moves. We can so consider the segment and the local reference like the same thing when we refer to the limb's orientation. In order to describe the orientation of each segment with respect to the global reference system we recur to the *Euler Angles*. Starting by the definition of these angles, by derivation, it is then possible to obtain the *Angular velocity* and *acceleration* for each segment. We will deal with this matter in the next chapter (4.5.2), about the Angular Kinematics definition.

3.1.2 Kinematics of Joints

In the human body, the Joints represent the natural conjunction between two different segments, forcing specific kinematical bonds and conditioning so the segments relative movement. In order to define the relative orientation of a segment respect to another we need to define three axis and three relative rotation (*flexion-extension*, internal-external and *abduction-adduction*). We will also deal with this in the next chapter, about Angular Kinematics.

3.2 Dynamics of Human Gait

With the term *Dynamics* of human gait we refer to the part of human movement study which deals with the causes of the motion, in contrast with the previous definition of Kinematics [Vaughan *et al*., 1992]. In the Dynamic field we differentiate between *forward* and *inverse* dynamics; the equations of motion give the relation between kinematics, motion, and kinetics, forces. We can use this relations defining two different approaches: the forward dynamic solves the motion starting from the forces, while the inverse dynamic calculates the forces from the knowledge of the motion [Otten, 2003].

3.2.1 Forces and Torques on the Joints

Starting by the knowledge of the Kinematics and knowing the external Forces' values, like the ground reaction forces, given by the force plates, and these due to the gravitational field[3], we can evaluate the forces and the torques exerted by the muscles and acting on the joints. This is the so-called *inverse dynamics* problem, aimed to calculate the joints forces and torques.

First of all, we need to define the idea of *Free Body Diagram* (*FBD*), or rather a diagram in which we consider the segment of interest separately from the other segment and the total body and from the environment too, drawing all the external forces acting on it (*Figure 3-2*).

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[3] In the next chapter (4.4) we will see how to calculate the Weight for each segment by knowing the *Anthropometric Parameters*

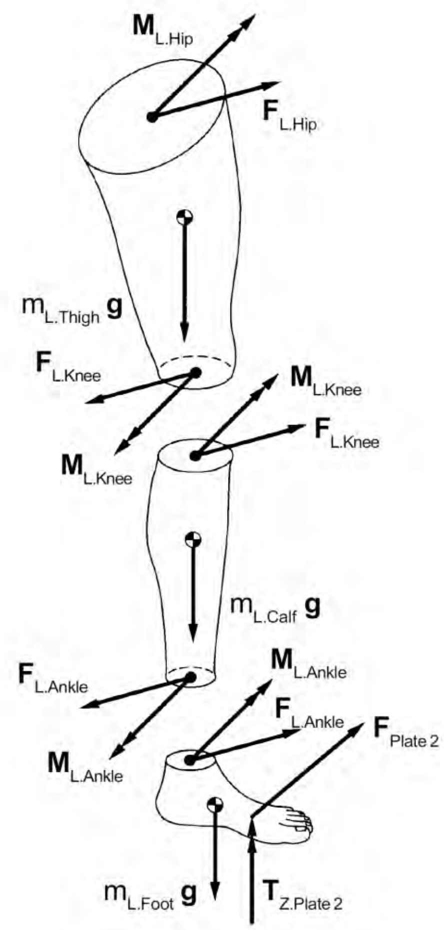

Figure 3-2. Exemples of Free Body Diagrams for Thigh, Calf and Foot [Vaughan *et al*., 1992]

Now we have to apply the *Vectorial Theorems* of motion referring to each segment's FBD; this law is explicated in two parts:

- *Linear Momentum Theorem*, stating the equilibrium of all the external forces acting on the segment and the linear momentum of the segment;
- *Angular Momentum Theorem*, claiming the equality of external moments acting on the segment about its Centre of Mass and the rate of change of the angular momentum of the segment [Vaughan *et al*., 1992].

3.3 Motion Capture System

The field of the Human Gait Analysis systems counts several methodologies to measure gait characteristics: stride analysis, angular kinematic analysis, force plate and foot pressure analysis and electromyographic (EMG) analysis.

The *stride analysis* use temporal sequence of stance and swing, measured instruments like stopwatch and ink, electromechanical tools or pressure-sensitive switches applied on the foot, calculating the time-distance variables. The *Angular Kinematic* analysis are performed using electrogoniometers, accelerometers, directly attached on the segments of interest, or optoelectronic techniques. *EMG* works recording muscle activation during the motion; it could be used with stride or angular analysis techniques and it is useful to understand the muscle kinetic activity. *Pressure plates* give the values of the load distribution beneath the foot during stance.

In our analysis, we recur to an *Optoelectronic* technique; this kind of system uses cameras for frames capture of the observed subject gait. The use of reference markers, directly positioned on the subject, is required in order to evaluate the location of joints. Before the markers capture phase a careful calibration of the system is required, while normally the used cameras are permanently installed in what we define –Gait Laboratory”.

In order to estimate the ground reaction forces and torques, Lab is also provided with *Force Plates*; using this kind of instruments it is also possible to evaluate the location of the point in which the reaction resultant force is exerted, or rather the *Centre of Pressure* (*COP*). Often force plates, as pressure plates too, are combined with kinematic measurements, in order to obtain kinetics (i.e. kinetic variable like joints torques) [Nordin & Franke, 2001].

3.3.1 UPC Biomechanics Lab

The UPC Biomechanics Lab of the Department of Mechanical Engineering is provided of an optoelectronic system constituted by 12 *OptiTrack™* cameras, by *NaturalPoint©*, FLEX:V100 R2 Model; these infrared LED devices allow the discrete capture of the 37 reflective markers positioned on the observed subject in specific locations, like in correspondence of the joints. We report, in *Figure 3-3*, a picture related with the used cameras.

Figure 3-3. *OptiTrack™ FLEX:V100 R2* cameras, by *NaturalPoint©* (http://www.naturalpoint.com)

The *ARENA®* software for Kinematic capture consents the real time visualization of the markers points along time for all the area in which the walking is performed; furthermore, the software allows the storage of the markers data in *.c3d* format files and elaborates markers' 3D trajectories, once the capture is ultimate. The provided output file is available for platform like the Matlab one, in order to perform all the required analysis.

The Lab is also provided with two *AMTI* force plates, *AccuGait* model, for the ground reaction forces measurement. Each force plate is provided of 4 sensors, one for each plate's corner; since the plate gives the force and moments components in the three directions (*x*, *y* and *z*), we can count twelve components of forces for each plate along time. The *NetForce* software takes the force plate data, giving as output a *.txt* file containing an array with the forces and the torques components (evaluated about the plate central axis) along time. The optical and the force measurements are revised, in way to make the coordinate system centre for the kinematical capture to match the centre of the first force plate. In the picture that follows (*Figure 3-4*) we report a view of the Lab, showing the cameras equipment, the force plates and the computer station for the data acquisition, while performing analysis on a normal male subject.

Figure 3-4. Normal male subject performing a walking in the UPC Gait Lab

3.4 Markers positioning and computational model

The Gait Analysis in our Lab is performed on subject wearing a suit with 37 attached passive markers, located as in the following table (*Table 1*) and as in the picture that follows (*Figure 3-5*):

1 - External right foot
2 - Right heel
3 - Right ankle
4 - Right tibia
5 - External right knee
6 - Right thighbone head
7 - Right hip bone
8 - External left foot
9 - Left heel
10 - Left ankle
11 - Left tibia
12 - External left knee
13 - Left thighbone head
14 - Left hip bone
15 - Sacrum
16 - Right high shoulder
17 - Right lateral shoulder
18 - Right elbow
19 - Right forearm
20 - Right wrist

21 - Right hand knuckle
22 - Right index knuckle
23 - Left high shoulder
24 - Right lateral shoulder
25 - Left elbow
26 - Left forearm
27 - Left wrist
28 - Left hand knuckle
29 - Left index knuckle
30 – Back
31 - Right ear
32 - High head
33 - Left ear
34 - Internal right foot
35 - Right foot big toe
36 - Internal left foot
37 - Left foot big toe

Table 3-1. Markers' locations list

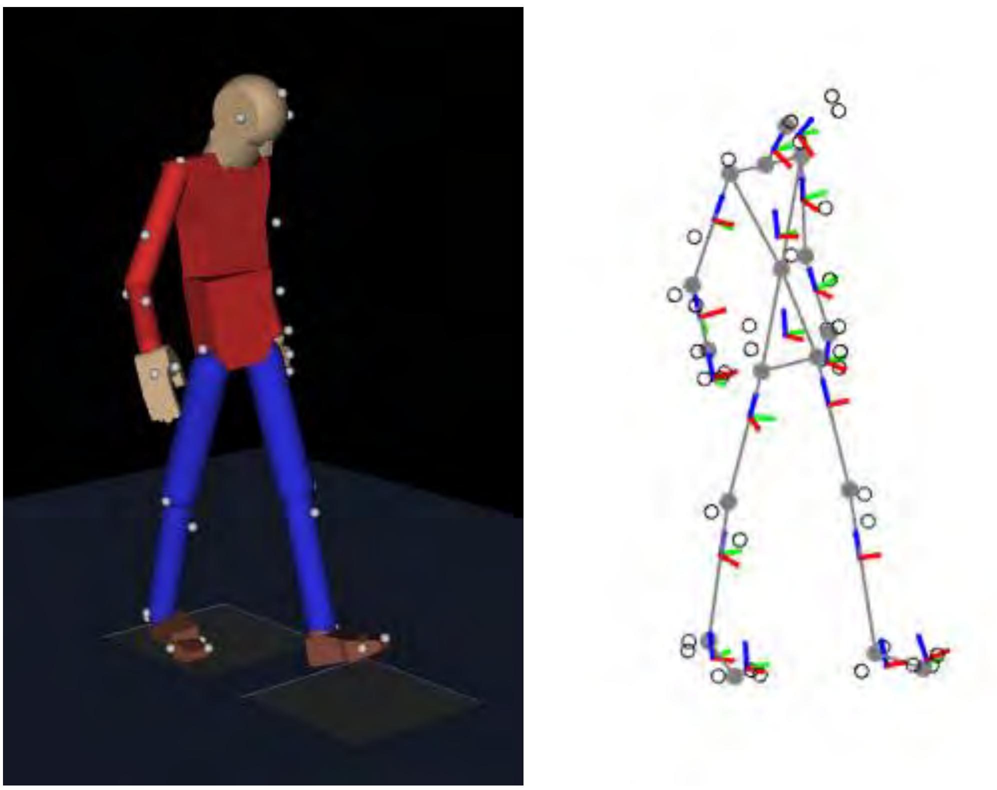

Figure 3-5. (a) Markers location; (b) Computational model (Cuadrado et al., 2011).

The model is composed by 18 segments, connected by spherical joints; in the *Figure 3-5.b* we report the Cartesian local systems for each segment. In the next chapter (4.4) we will report information about how the geometric parameters of the model are obtained, the applied anthropometric measurements and the used filtering techniques. The provided results will not be consistent[4]: starting by the markers’ trajectories along time we provide the model coordinates, using algebraic relations; the obtained values are not kinematically consistent, since errors, due to the motion capture process, are present [Cuadrado *et al*., 2011]. Actually we are able to impose kinematic consistency in Matlab environment just for the 2D model, so it will be impossible to provide consistent kinematics for our project.

3.5 *Graphical User Interface* (*GUI*) of Matlab

For the development of our project, we used the *Graphical User Interface* (*GUI*) tool of Matlab. A GUI consists in a display containing windows with controls, the “components”, in order to offer several tasks to the user that does not need to develop Matlab routines or to insert commands directly from the command line. Finally, the user has just to create the desired GUI environment, without needing to understand the way of functioning of the used tasks.

The user can select from a set of tools like menus, toolbars, push buttons, radio buttons, list boxes or sliders, with also the opportunity of communicating with external sources, like reading and writing files or showing tables and plots, or with other GUIs. Typically, GUIs are made in way to wait for the user to execute some control, responding to the performed request acting on one or more user-written routines, called “callbacks” (these routines “call back” to Matlab in order to perform actions); this is called event-driven programming. Each callback can be activated by user actions like pressing buttons, selecting a menu item, typing a string or a value, etc. in an asynchronous way, or rather being triggered by external events: in our case, the user can interact directly with the created GUI, but this can then respond acting with external aimed actions like creating a file or calling another computer device.

In order to develop a new GUI, the developer needs to understand since the start what kind of requests are needed to be satisfied, knowing totally the inputs, the outputs, the displays, the needed functions and the application that the GUI has to control. Then it is needed to create the GUI’s routines and check their correct and consistent way of working and, finally, it is

[4] Definition of *consistency* in the first chapter (1.4)

needed to test the created interface. The diagram reported in the picture that follows (*Figure 3-6*) shows what should be the steps in the GUI creation process.

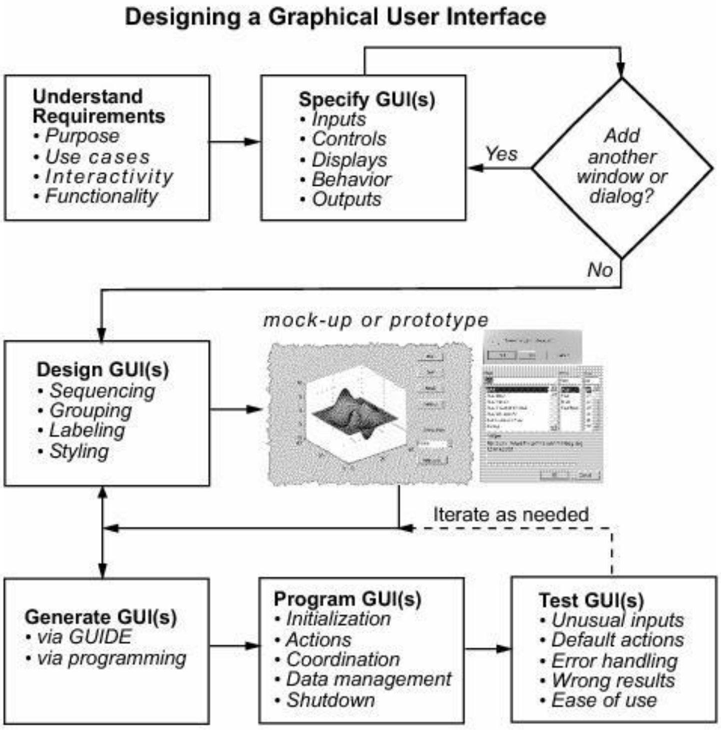

Figure 3-6. Process of creation of a GUI (www.mathworks.com)

A Matlab GUI could be created by following two different approaches:

1) Using the GUIDE tools (GUI Development Environment), an interactive GUI construction kit called by writing –guide” in the Matlab command line;
2) Creating routine files that generate GUIs as functions or scripts (programmatic GUI construction).

In our work, we followed the first approaches that provides initially an empty figure that the GUI developer can populate with the required components. Finally, we obtain two different files: one saved like figure (FIG-file) and one like code file, recalling each other automatically when executed.

In the second approach a code file is created; this file, when executed, defines all the GUI components and creates automatically the corresponding figure, not saved but provided every time the routine runs [MathWorks, 2011].

3.5.1 C3D server

In order to elaborate *.c3d* format file, containing kinematical data, it is needed to add the *C3D directory* to the MATLAB path; in this directory we can find Matlab functions used to activate and use *Motion Lab Systems* (*MLS*) *C3Dserver* as a *COM* object (Component Object Model) in MATLAB, needed to access to all of the functions within the C3Dserver.

The Motion Lab Systems C3Dserver is a 32-bit C3D Software Development Kit (SDK) for Microsoft Windows™ environments, aimed to the simplification of C3D file programming. It makes possible the access to the data, creating, modifying and processing it [Motion Lab Systems, 2011].

In this work, the *2nd version* of the c3d directory is used, implemented by *Matthew R. Walker* and *Michael J. Rainbow* [*Motion Analysis Laboratory Shriners Hospitals for Children* – Erie PA (USA); April 21, 2006] and furnished for free like evaluation version (the commercially licensed version differ from the evaluation one just in the speed of execution).

CHAPTER 4

GRAPHICAL USER INTERFACE FOR GAIT ANALYSIS

The general purpose of our work is the development of an interface for Gait Analysis, in order to provide a platform for the global elaboration of both kinematical and force plate measurements data; this kind of data is respectively provided in *.c3d* and *.txt* format by the Lab software: our routines will operate in a way to process the stored data, performing operations like the synchronization of both cameras capture and force plates information and the definition of a set of features that allows to extrapolate all the data of interest in the Gait Analysis field. All the performed operations will be described in the following sections.

The user will operate on a *GUI* (*Graphical User Interface* built using Matlab®) that allows to plot data, to visualize a gait video and to export information. The Matlab routines integrated in our GUI provide, in succession, to the following instances:

- Reconstruction of markers position and trajectories, exporting them in a *.mat* file and filtering the data, starting by the markers sampling made by IR cameras;
- Synchronization of the capture (*.mat*) and the force plate (*.txt*) data;
- Loading of Anthropometric measurements and *BSPs* (*Body Segment Parameters*), selecting between two different BSP models;
- Extrapolation of all the information related with *kinematic* (joints, centres of mass (CM), centre of pressure (COP), anatomical joints angles (AJA), segments velocity and acceleration) and *force plate measurementss* (Forces and Torques).

The user can act directly on the data processing, setting:

- The BSP model (choosing between the *Vaughan – Ambrosio* and the *Dumas* one);
- The Anthropometric measurements, selecting a database among *Normal Male* and *Normal Female* provided by Vaughan and a set of measurements taken on a male subject in Lab;
- The filter, selecting between *SSA* or *Butterworth*, and filtering features.

The GUI also contains a set of tools that could be useful for the user in the elaboration phase (data processing and filtering) and in the visualization phase; these will be showed in the next chapter, in which we will describe accurately the GUI functioning.

4.1 Kinematical data processing

In this first phase, the *.c3d* file is opened in the c3dserver domain. The created Matlab routines extract kinematical data and reconstruct both the *Time* array, starting by the number of frame, and the *Trajectories* of the markers. In this step, the Matlab routine establishes also the corrected markers position along time, producing a final video in which markers are shown in a 3D space: in case of incorrect reconstruction, the markers are represented in red; otherwise, if everything is working, the markers points are shown in blue. In *Figure 4-1* it is reported a frame from the markers video, in which there is no incorrect marker tracking (no red markers), extracted from our GUI.

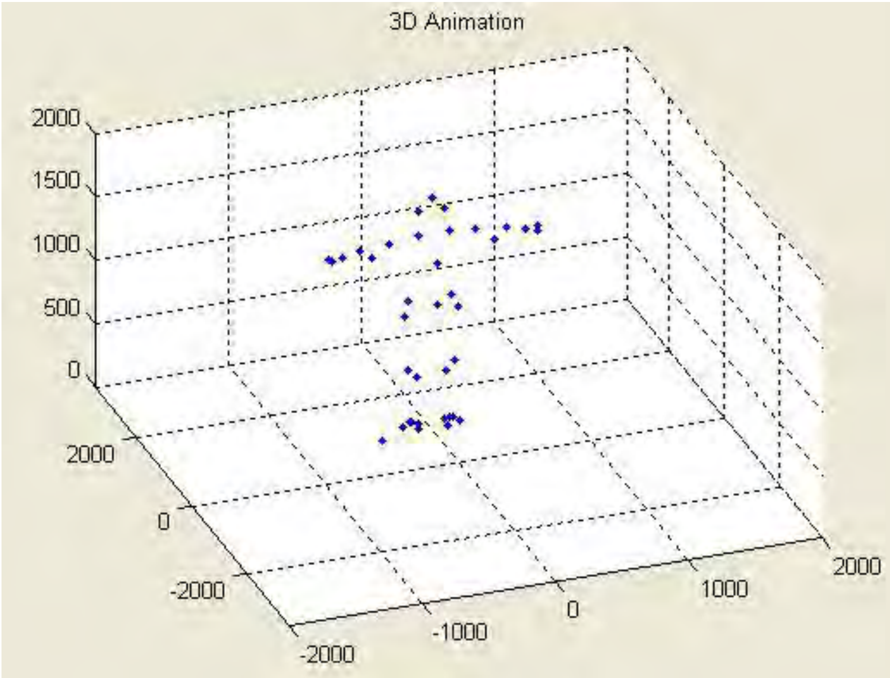

Figure 4-1. Frame from markers video, taken from the created GUI

4.2 File synchronization

Since the files containing Kinematical data (*.mat*) and force plate measurements (*.txt*) are taken from different software packages, we need to synchronize the contained information. In order to make this, during the data recording, at the beginning of the gait, three hammer strokes are performed on one force plate; the hammer is provided of a marker. The synchronization is made evaluating both the hammer's marker trajectory and the force plate's registration in the period in which the strokes are performed, considering that the minimum vertical value in marker trajectory corresponds to a maximum of the measured vertical force; we have, so, three points of interest, at the starting of the gait (the three strokes). The routine works in a way to line up the contents of the two files matching the three time events. At the end of this step, we obtain *rm.dat* file, containing x, y and z values of each marker along time, and *FPL1.dat* and *FPL2.dat*, concerning x, y and z components of Forces and Torques of the two force plates along time.

4.3 Filtering

Several errors, both of random or of systematic nature, are introduced in biomechanical analysis by the motion capture systems; these kind of errors causes high-frequency low-amplitude noise, that could appear in the recorded displacement signal, being then even amplified by the differentiation made in order to obtain velocities and accelerations [Silva *et al.*, 2004; Vaughan, 1982]. This problem could bring errors in the Gait Analysis, particularly performing the *Inverse Dynamic Analysis* (IDA) [Vaughan, 1982; Alonso *et al.*, 2005]. To avoid this phenomenon, it is necessary to filter the displacement signal prior to differentiation.

Among the filtering techniques, we are interested in digital *Butterworth* filters and in a technique called *Singular Spectrum Analysis* (*SSA*): the Butterworth filters have not the best performance in non-stationary situations, while the SSA, based on time-frequency transforms, is better for non-stationary signals filtering [Alonso *et al.*, 2010].

With the created GUI the user could choose between these two filtering techniques, setting *order* (N), *sample frequency* (f_s, normally set at 100 Hz) and *cut-off frequency* (f_c) for the Butterworth filter and the *window length* for the SSA.

After this step, the signals contained in the *rm.dat* file are filtered, avoiding consequent errors in markers velocities and accelerations calculation and in obtaining the other parameters too (i.e. Joints displacements, velocities and accelerations), since all of kinematical data is obtained starting by markers information.

4.4 BSP parameters

Body Segment Parameters (*BSP*) describe the body characteristics, like geometry and inertial properties, defining the limbs' masses, the centres of mass, the moments of inertia and all the related parameters either of each segment and of the total body. Typically we can find, in literature, BSPs obtained by scaling rules applied to cadavers; however, this kind of studies provide BSP values that could differ among them more than 40% [Pearsall & Costigan, 1999]. Furthermore, it is impossible to obtain a complete information, since there are no simple ways to provide general parameters for special populations (like children or obese adults). In Gait analysis, the Body Segment Parameter values are necessary in performing both forward and inverse dynamics analysis.

There are different methods used in order to evaluate BSP; the most common are:

- Cadaver averages [Braune & Fischer, 1889; Dempster, 1955], as told before;
- Mathematical modelling [Hanavan, 1964; Hatze, 1980];
- Scans using gamma rays, axial tomography or magnetic resonance imaging [Brooks & Jacobs, 1975; Erdmann, 1989; Zatsiorsky & Seluyanov, 1985]
- Direct kinematic measurements [Ackland, Blanksby, & Bloomfield, 1988; Dainis, 1980; Vaughan, Andrews, & Hay, 1982].

In what follows, a list of our *Body Segment Parameters*:

- *Mas*s, in kilograms, for each segment (i.e., thigh, calf, foot);
- *Centre of mass* location for each segment, related to a specified anatomical landmarks (i.e., proximal or distal joints);
- *Moments of inertia* of the segments about three orthogonal [Vaughan *et al.*, 1992].

In this study, we use two different sets of BSPs: the first one mixes both the models by *Vaughan* and *Ambrosio*, while the latter is constituted by the *Dumas* model.

4.4.1 *Vaughan – Ambrosio* BSP model

Ambrosio

Ambrosio & Kecskeméthy (2007) modeled the human body using 16 rigid bodies, reported in *Table 1* with reference to the following illustration (*Figure 4-2*); in the first column of the table, we can find the description of the segments; the second column reports the *ith* number associated to each segment, with reference to the *Figure 4-2a*; in the two following columns there are the geometric characteristics of the rigid bodies: the segments length and the location of the centres of mass, referred to the proximal joint; these latter could be expressed by two different dimensions, in case of the CM location is referred to two different joints d_i for proximal and $\underline{d_i}$ distal joints. For the geometric parameters, refer to the *Figure 4-2b*. In the last two columns we report the inertial parameters, or rather the mass of the *ith* segment and its three moments of inertia, referred to the local coordinate system.

The model is made of an open loop structure, counting 44 degrees-of-freedom (38 rotations about 26 revolute joints and 6 universal joints and 6 degrees-of-freedom related to the free body rotations and translations of the base body).

Description	Body	Length	CM location		Mass (kg)	Moments of Inertia (10^{-2} kg·m^2)
	i	***L_i (m)***	***d_i (m)***	***$\underline{d_i}$ (m)***	***m_i***	**$(I_{xx}/ I_{yy}/ I_{zz})_i$**
Lower Torso	1	0.275	0.064	0.094	14.200	26.220/13.450/26.220
Upper Torso	2	0.294	0.101	0.161	24.950	24.640/37.190/19.210
Head	3	0.128	0.020	0.051	4.241	2.453/2.249/2.034
R Upper Arm	4	0.295	0.153	-	1.992	1.492/1.356/0.248
R Lower Arm	5	0.250	0.123	-	1.402	1.240/0.964/0.298
Hand	13	0.185	0.093	0.045	0.489	0.067/0.146/0.148
L Upper Arm	6	0.295	0.153	-	1.992	1.492/1.356/0.248
L Lower Arm	7	0.376	0.180	-	1.892	1.240/0.964/0.298

Hand	14	0.185	0.093	0.045	0.489	0.067/0.146/0.148
R Upper Leg	8	0.434	0.215	-	9.843	1.435/15.940/9.867
R Lower Leg	9	0.439	0.151	.	3.626	1.086/3.830/3.140
Foot	14	0.069	0.271	0.035	1.182	0.129/0.128/2.569
L Upper Leg	10	0.434	0.215	-	9.843	1.435/15.940/9.867
L Lower Leg	11	0.439	0.151	.	3.626	1.086/3.830/3.140
Foot	16	0.069	0.271	0.035	1.182	0.129/0.128/2.569
Neck	12	0.122	0.061	-	1.061	0.268/0.215/0.215

Table 4-1. Physical characteristics of anatomical segments and rigid bodies for the 50th percentile human male. The dimensions and positions of the centre of mass locations, with respect to the proximal joint with reference to *Figure 4-2*, reported in a row [Ambrosio & Kecskeméthy, 2007].

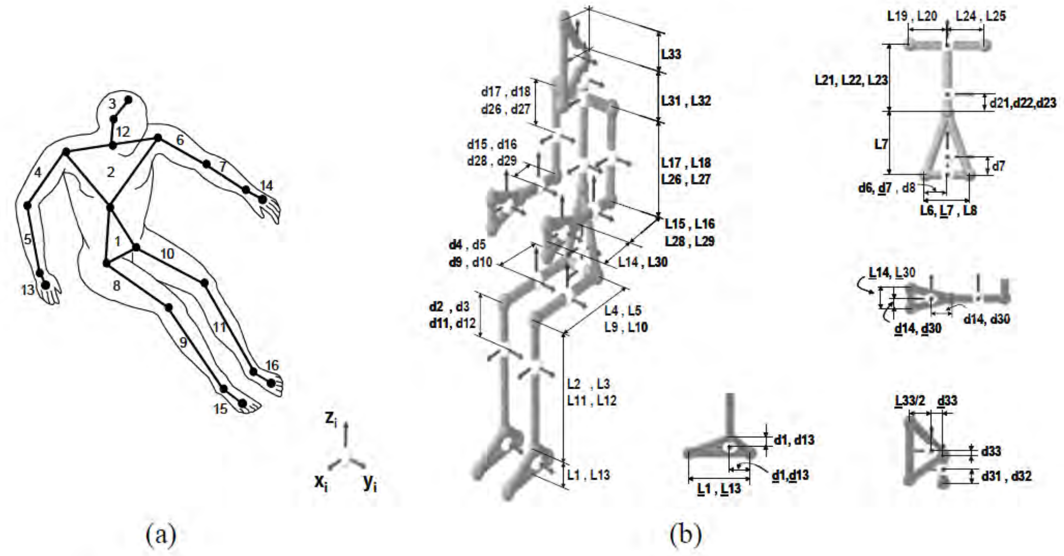

Figure 4-2. Biomechanical model with 16 anatomical segments: (a) Topology of the model; (b) Reference for the length and centre of mass of each anatomical segment [Ambrosio & Kecskeméthy, 2007].

The provided model is general-purpose and it can so be used for any kind of kinematic and dynamic analysis. In order to apply it to a specific individual it is needed to scale the anatomical segments for each case, considering that Ambrosio's model concerns the 50th percentile human male. For his work, Ambrosio used non-dimensional scaling factors directly calculated on the subject's measurements, relating these with data in *Table 4-1*. These scaling factors are defined as:

$$X_{L_i} = \frac{L_i^{n^{th}}}{L_i^{50^{th}}}; X_{m_i} = \frac{m_i^{n^{th}}}{m_i^{50^{th}}}; X_{I_i} = X_{m_i} \cdot X_{L_i}^2 \tag{1.1}$$

Where $X_{L\,i}$, $X_{m\,i}$ and $X_{I\,i}$ are the scaling factors of the length, mass and moments of inertia calculated for the *ith* segment. If the length and mass of each segment of the subject are not available, the calculation of $X_{L\,i}$ and $X_{m\,i}$ can be provided respectively as the ratio between heights and the ratio between total body weights. All the dimensions are scaled referring to the length scaling factor, even the CM location. This procedure is valid just for scaling subjects of the same gender (male) and with anthropometric characteristics similar to the reference model [Ambrosio & Kecskeméthy, 2007].

Vaughan

In their work, Vaughan *et al.* (1992) had chosen six segments: *thigh*, *calf*, and *foot* on both the left and right sides, with the assumption of rigidity for each segment (constant dimensions during the motion, even if well known that the foot is not a single rigid segment, changing shape while performing the gait).

In order to develop a model with the features of personalization for each individuals and accuracy, Vaughan *et al.* (1992) developed a technique based on direct measure of parameters made on lower limbs, reported in *Figure 4-3*.

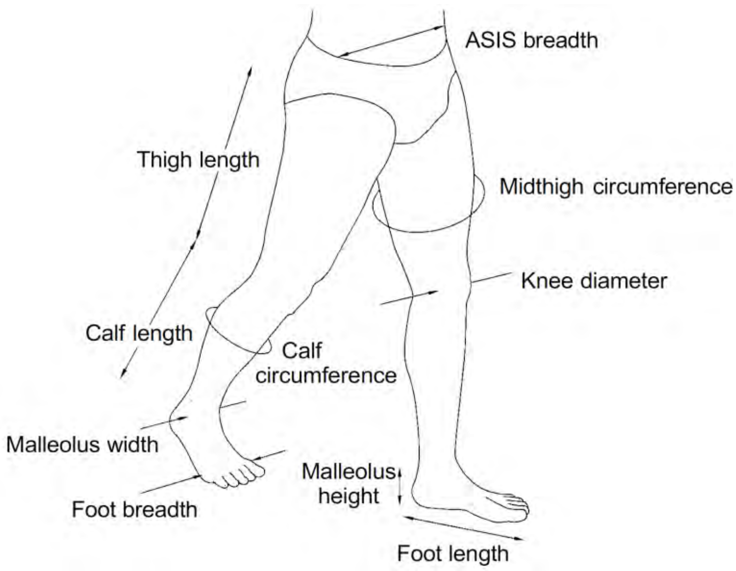

Figure 4-3. The anthropometric measurements of the lower extremity that are required for the prediction of body segment parameters (masses and moments of inertia) [Vaughan *et al.*, 1992].

There are 20 measurements that are needed (19 lengths and the subject's total body mass), describing, in detail, the characteristics of the subject's lower limbs.

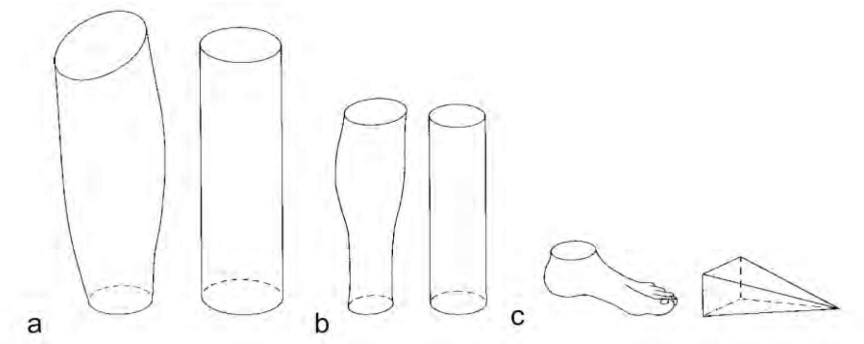

Figure 4-4. Lower extremity body segments and their geometric counterparts: (a) thigh; (b) calf; (c) foot [Vaughan *et al.*, 1992].

Vaughan et *al.* (1992) started considering that each segment mass is related not only to the subject's total body mass, but also to the dimensions of the limb; they considered that the shapes of the thigh and calf could be represented by cylinders while the shape of the foot is similar to a right pyramid (*Figure 4-4*), calculating this way the masses of each single geometric segment, assuming the segment density among subjects to be invariant and using the linear dimensions as predictors of the segment masses. The authors based their equations on studies by Chandler *et al.* (1975), performed on six cadavers.

For calculating the moments of inertia, considering as before the thigh and calf similar to a cylinder and the foot similar to a right pyramid, Vaughan *et al.* (1992) started from general geometric equations, related to the principal orthogonal axis (in *Figure 4-5*, the principal orthogonal axis for the thigh and a cylinder).

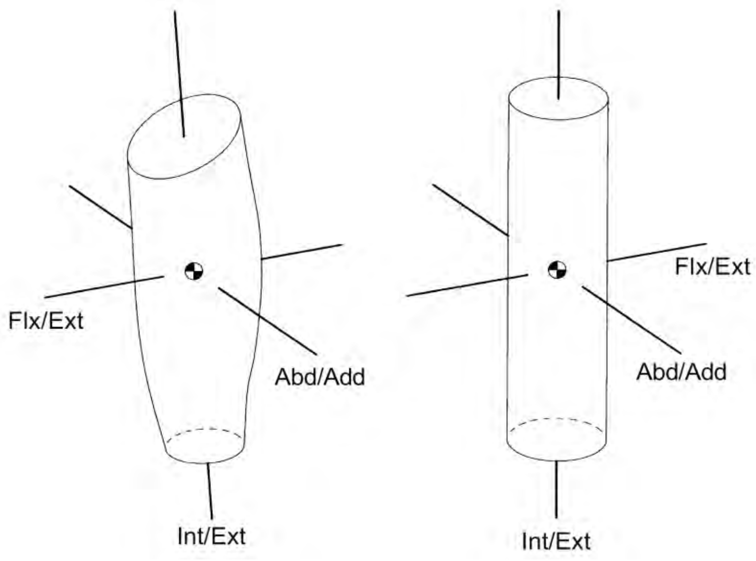

Figure 4-5 Principal orthogonal axis for the thigh and a right cylinder [Vaughan *et al.*, 1992].

Relatively to the centres-of-mass (*CM*) data, Vaughan *et al.* (1992) expressed them as ratios, based on knowing the segment endpoints for the limbs. The CM points are located in the middle of the segments and their ratio is referred to the segment length. These parameters are also obtained from cadavers studied by Chandler *et al.* (1975).

As reported before, all the Vaughan's model BSPs are calculated starting by 20 anthropometric measurements, reported in the *Table 4-2*:

Parameter number	Name
A_1	Total body mass
A_2	Anterior superior iliac spine (ASIS) breadth
A_3	Right thigh length
A_4	Left thigh length
A_5	Right midthigh circumference
A_6	Left midthigh circumference
A_7	Right calf length
A_8	Left calf length
A_9	Right calf circumference
A_{10}	Left calf circumference

A_{11}	Right knee diameter
A_{12}	Left knee diameter
A_{13}	Right foot length
A_{14}	Left foot length
A_{15}	Right malleolus height
A_{16}	Left malleolus height
A_{17}	Right malleolus width
A_{18}	Left malleolus width
A_{19}	Right foot breadth
A_{20}	Left foot breadth

Table 4-2. Anthropometric Data for Calculating Body Segment Parameters and for Predicting Joint Centres and Segment Endpoints [Vaughan *et al.*, 1992]

Using these parameters it is possible to evaluate all the BSPs following the tables in a row (masses and CMs in *Table 4-3*, moments of inertia in *Table 4-4*):

Mass.R.Thigh = (0.1032) * A1 + (12.76) * A3 * A5 * A5 - 1.023; **Mass.L.Thigh = (0.1032) * A1 + (12.76) * A4 * A6 * A6 - 1.023;** **Mass.R.Calf = (0.0226) * A1 + (31.33) * A7 * A9 * A9 + 0.016;** **Mass.L.Calf = (0.0226) * A1 + (31.33) * A8 * A10 * A10 + 0.016;** **Mass.R.Foot = (0.0083) * A1 + (254.5) * A13 * A15 * A17 - 0.065;** **Mass.L.Foot = (0.0083) * A1 + (254.5) * A14 * A16* A18 - 0.065;**
CG_Ratio.R.Thigh = 0.39; **CG_Ratio.L.Thigh = 0.39;** **CG_Ratio.R.Calf = 0.42;** **CG_Ratio.L.Calf = 0.42;** **CG_Ratio.R.Foot = 0.44;** **CG_Ratio.L.Foot = 0.44;**

Table 4-3. Equations to Predict the Masses and Centres of Gravity for the Thigh, Calf and Foot [Vaughan *et al.*, 1992]

I_FlxExt.R.Thigh = 0.00762 * A1 * (A3 * A3 + 0.076 * A5 * A5) + 0.01153; **I_FlxExt.L.Thigh = 0.00762 * A1 * (A4 * A4 + 0.076 * A6 * A6) + 0.01153;** **I_AbdAdd.R.Thigh = 0.00726 * A1 * (A3 * A3 + 0.076 * A5 * A5) + 0.01186;** **I_AbdAdd.L.Thigh = 0.00726 * A1 * (A4 * A4+ 0.076 * A6 * A6) + 0.01186;** **I_IntExt.R.Thigh = 0.00151 * A1 * A5 * A5 + 0.00305;** **I_IntExt.L.Thigh = 0.00151 * A1 * A6 * A6 + 0.00305;**
I_FlxExt.R.Calf = 0.00347 * A1 * (A7 * A7 + 0.076 * A9 * A9) + 0.00511; **I_FlxExt.L.Calf = 0.00347 * A1 * (A8 * A8 + 0.076 * A10 * A10) + 0.00511;** **I_AbdAdd.R.Calf = 0.00387 * A1 * (A7 * A7 + 0.076 * A9 * A9) + 0.00138;** **I_AbdAdd.L.Calf = 0.00387 * A1 * (A8 * A8 + 0.076 * A10 * A10) + 0.00138;** **I_IntExt.R.Calf = 0.00041 * A1 * A9 * A9 + 0.00012;** **I_IntExt.L.Calf = 0.00041 * A1 * A10 * A10 + 0.00012;**
I_FlxExt.R.Foot = 0.00023 * A1 * (4 * A15 * A15 + 3 * A13 * A13) + 0.00022; **I_FlxExt.L.Foot = 0.00023 * A1 * (4 * A16 * A16 + 3 * A14 * A14) + 0.00022;** **I_AbdAdd.R.Foot = 0.00021* A1* (4 *A19 *A19 + 3 * A13 * A13) + 0.00067;** **I_AbdAdd.L.Foot = 0.00021 * A1 *(4 *A20 *A20 + 3 * A14 * A14) + 0.00067;** **I_IntExt.R.Foot = 0.00141 * A1 *(A15 * A15 + A19 * A19) - 0.00008;** **I_IntExt.L.Foot = 0.00141 * A1 * (A16 * A16 + A20 * A20) - 0.00008;**

Table 4-4. Equations to Predict Moments of Inertia (I) for the Thigh, Calf, and Foot [Vaughan *et al.*, 1992]

Finally, Vaughan calculated the lengths of the lower part segments, obtaining them in terms of positions of distal joints in relative coordinates starting by the 15 marker positions; in this phase it is needed a prior definition of Kinematics (we will discuss it later, tackling the definition of the orientation matrix and joints position in the *Kinematical analysis* section).

Vaughan – Ambrosio model

In this work, we use a model that is a mix of both Vaughan's and Ambrosio's ones; the total body model is constituted by 16 segments (10 for the upper part, 6 for the lower one), considering right and left side: *Head*, *Neck*, *Torso*, *Pelvis*, *Arm*, *Forearm*, *Hand*, *Thigh*, *Leg* and *Foot*. We can choose the anthropometric starting parameters among a set of values made of *Normal Male*, *Normal Female*, both furnished by Vaughan[5] and measurements taken on a male subject in Lab (*Table 4-5*); in any case, they are scaled later according to markers

[5] http://isbweb.org/software/movanal.html

position. We consider another 2 segments, the *right* and *left forefeet*, for a total of *18 segments*.

Anthropometric measurement	Value *Vaughan Normal Male*	Value *Vaughan Normal Female*	Value *Lab Normal Male*	Units
Total body mass	64.9000	51.2000	74.0000	kg
Anterior superior iliac spine (ASIS) breadth	0.2400	0.2480	0.2900	m
Right thigh length	0.4600	0.3660	0.4050	m
Left thigh length	0.4650	0.3700	0.4050	m
Right midthigh circumference	0.4500	0.4700	0.4900	m
Left midthigh circumference	0.4400	0.4650	0.4900	m
Right calf length	0.4300	0.3720	0.4100	m
Left calf length	0.4300	0.3600	0.4100	m
Right calf circumference	0.3650	0.3220	0.3750	m
Left calf circumference	0.3650	0.3220	0.3750	m
Right knee diameter	0.1080	0.0980	0.0990	m
Left knee diameter	0.1120	0.0960	0.0990	m
Right foot length	0.2600	0.2450	0.2750	m
Left foot length	0.2600	0.2430	0.2750	m
Right malleolus height	0.0600	0.0720	0.0870	m
Left malleolus height	0.0600	0.0660	0.0870	m
Right malleolus width	0.0740	0.0630	0.0730	m
Left malleolus width	0.0730	0.0640	0.0730	m
Right foot breadth	0.0980	0.0900	0.0910	m
Left foot breadth	0.0960	0.0880	0.0910	m

Table 4-5. Anthropometric Data Required to Predict Body Segment

The geometric parameters of the model, lengths of the segments and positions of the centres of mass, are obtained, for the lower limbs, by applying Vaughan's model equations (*Tables 4-3, 4-4*) to the anthropometric measurements and, for the upper part of the body, by scaling Ambrosio's data (*Table 4-1*) according to the mass and height of the subject and to his model (equation ***(1.1)***); furthermore, centre of mass's data, for upper body, are also scaled referring to a scaling factor obtained from the ratio between lower limbs lengths, calculated on the same segment (the *thigh*), using both models (Vaughan and Ambrosio); this operation[6] is included in the computation of the X_{L_i} factor. The inertial parameters are obtained, for the lower limbs, using Vaughan's equations and, if available, using a correction based on data coming from densitometry (*DXA.dat* file), actually available just for the *Lab Normal Male* set; for the upper part of the body, the scaling method, according with Ambrosio, is used again, using both the X_{L_i} (as defined before) and the X_{m_i} scaling factors. Regarding the metatarsus data, we obtain CM information dividing the foot length in two parts and then we calculate the inertial parameters in order to keep the global inertial parameters constant.

4.4.2 *Dumas* BSP model

In their studies, Dumas *et al.* (2007a) analyzed data from McConville *et al.*(1980) in order to adjust them making them correspond to joint centres and to conventional segment axis. Dumas provided scaling equations for both males and females, obtaining BSPs available for the conventional 3D segment coordinate systems (SCSs).

McConville *et al.* (1980) and Young *et al.* (1983) provided the 3D location for each Centre of Mass, the principal moments of inertia and orientations of the principal axis of inertia, referring to anatomical axis, for 30 years old male and female populations, chosen in order to represent the entire stature/weight distribution. These studies were performed on living subjects, using stereo-photogrammetric technique which provided the position of centre of mass with an accuracy of 5.6%, if compared to measurements from six cadavers [McConville and Clauser, 1976]. Since the anatomical axis in these latter studies differ from the

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[6] $\mathrm{X}_{L_i} = \dfrac{L_i^{n^{th}}}{L_i^{50^{th}}} \cdot \dfrac{L_{Vaughan}}{L_{Ambrosio}}$, where $L_{Vaughan}$ and $L_{Ambrosio}$ are respectively the medium length of the right and the left thighs calculated with Vaughan and Ambrosio.

conventional axis used in the segment SCSs system [*Cappozzo et al.*, 1995; *Wu et al.*, 2002, 2005], the provided data have been used for dummies [Schneider *et al*., 1983] but they were never been not widely used for movement analysis. Dumas operated on McConville *et al*.'s (1980) and of Young et al.'s (1983) data in order to obtain BSPs referred to the conventional SCSs and provide general scaling equations.

The joints centres are estimated starting by selected anatomical landmarks [*Figure 4-6*, McConville et *al.*, 1980], using the same Anthropometric measurements set reported in the previous section, or rather ―Vaughan Normal Male", "Vaughan Normal Female" and ―Lab Normal Male", with reference to the *Table 4-5*. The SCSs are obtaining referring to the literature [Cappozzo *et al.*, 1995; Rao *et al.*, 1996; Wu *et al.*, 2002, 2005]. The adjustments are related to nine segments: *Head & Neck*, *Torso*, *Pelvis*, *Arm*, *Forearm*, *Hand*, *Thigh*, *Leg* and *Foot*, with the assumption of symmetrical limbs for right and left side, counting in all 15 body segments. Finally, Dumas *et al.* (2007a) consider Thorax plus Abdomen like a single segment, the *Torso*.

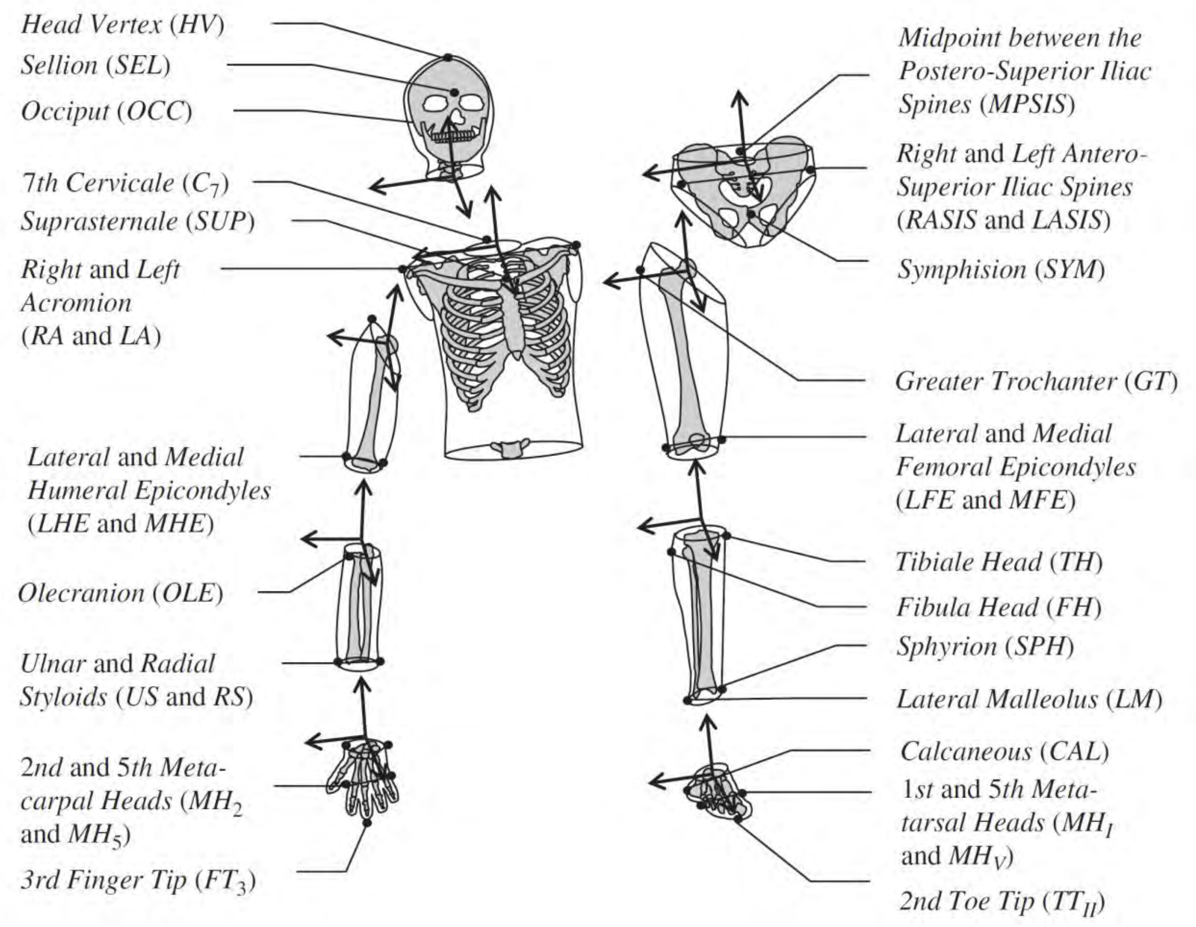


Figure 4-6. Anatomical landmarks [Dumas *et al.*, 2007a]

In our work, the lengths of the segments, for the Dumas' model, are taken directly from measurements made on human limbs and are not obtained starting by standard tables, considering mass and height and applying scaling factors neither reconstructed starting by markers position, like in Vaughan - Ambrosio's model.

For *Arm*, *Forearm*, *Thigh* and *Leg*, the segment length *L* is measured as the distance between the proximal and the distal joint centres. For the *Head & Neck*, the segment length is the distance between the *Cervical Joint Centre* (*CJC*) and the *HV*. For the *Hand*, the segment length is the distance between the *Wrist Joint Centre* (*WJC*, estimated as the midpoint between the *US* and *RS*) and the midpoint between the MH_2 and MH_5. An alternative segment length is between the *WJC* and the 3rd Finger Tip (*FT3*). For the *Foot*, the segment length is the distance between the *Ankle Joint Centre* (*AJC*, estimated as the midpoint between the *LM* and *SPH*) and the midpoint between the MH_I and MH_V. An alternative segment length is between the *CAL* and the 2nd Toe Tip (TT_{II}). For the *Pelvis*, the segment length is the distance between the *Lumbar Joint Centre* (*LJC*, according to Reed *et al.*, 1999) and the projection of the *Hip Joint Centre* (*HJC*, Reed *et al.*, 1999) in sagittal plane. An alternative segment length is the *Pelvis Width* (i.e. the distance between the *RASIS* and the *LASIS*). For the Torso, the segment length is the distance between the *CJC* and the *LJC*. An alternative segment length is the *Thorax Width* (i.e. the distance between the C_7 and the *SUP*) [Dumas *et al*., 2007a].

For this model, the user also has to select the *gender* of the analyzed subject (*M*, male, or *F*, female) and to insert the subject *body mass* (in kg); the adjusted BSPs scaling equations are given in *Appendix A* (*Table A-1*) (alternative origins and/or segment lengths for the *Torso*, *Hand*, *Pelvis* and *Foot* are also provided). With the notation (i) we indicate that the product of inertia is negative.

Later, the authors [Dumas *et al.*, 2007b] found a mistake in the estimation of the position for *Head Vertex* (*HV*). The correct position results in modified *Head & Neck* Segment Coordinate Systems (SCS) and in a modified segment length; the right data are reported in *Appendix A* (*Table A-2*).

4.5 Kinematical analysis

As a result of the previous steps we obtain filtered signals concerning markers trajectories along time and a complete definition of the body model composition. It is possible, in this step, to obtain all the kinematical data of interest, needed for performing Gait Analysis.

4.5.1 Linear Kinematics

The first operation that we have to define at this point is how to calculate the **uvw** reference systems for each segment, in order to predict the positions of joints centres; starting by 3D marker positions we use external landmarks to predict internal skeleton positions. The steps to be followed are:

1. The selection of three markers related to the segment of interest;

2. The creation of orthogonal **uvw** reference system based on the defined three markers, that are the vectors indicating the directions of our local coordinate system ($x_i y_i z_i$);

3. The application of the prediction equations based on anthropometric measurements and the **uvw** reference system to estimate the joint centre position [Vaughan *et al.*, 1992].

   In this work we narrow in reporting just the general procedure of working, expressed from the three points before, while we don't report the equations based on anthropometric measurements used in the Matlab routine (i.e. for the lower body we use equations reported in Vaughan's work), by Chandler *et al.* (1982).

In what follows, we give an example of how to create the **uvw** reference system and then find the joint centre position on the *right foot*:

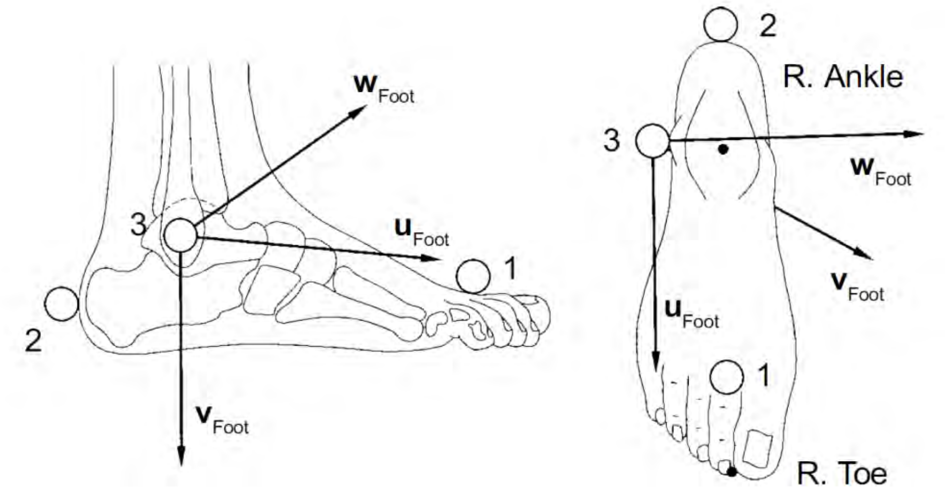


Figure 4-7. The three markers (1, 2, and 3) which define the position of the foot in 3- D space: (a) side view; (b) view from above. The uvw reference system may be used to predict the position of the ankle and toe [Vaughan *et al.*, 1992].

*<u>Example</u>: From the figure above (Figure 6) we can define the unit vector triad **uvw** for the right foot as follows, starting by the position of the three markers ($\mathbf{p}_1$, $\mathbf{p}_2$ and $\mathbf{p}_3$):*

$$\mathbf{u}_{\mathbf{R,foot}} = (\mathbf{p}_1 - \mathbf{p}_2) / |\mathbf{p}_1 - \mathbf{p}_2| \tag{4.2}$$

$$\mathbf{w}_{\mathbf{R,foot}} = \frac{(\mathbf{p}_1 - \mathbf{p}_3) \times (\mathbf{p}_2 - \mathbf{p}_3)}{|(\mathbf{p}_1 - \mathbf{p}_3) \times (\mathbf{p}_2 - \mathbf{p}_3)|} \quad \textbf{(4.3)}$$

$$\mathbf{v}_{\mathbf{R,foot}} = \mathbf{w}_{\mathbf{R,foot}} \times \mathbf{u}_{\mathbf{R,foot}} \quad \textbf{(4.4)}$$

Starting by these equations it is then possible to define the right ankle and the right toe positions [Vaughan et al., 1992].

Operating in this way, it is then possible to define the positions along time for all the joints (*r0.dat* file) and the **uvw** reference system for all the body limbs. Finally, we obtain a matrix containing the orientations of all the segments during the gait (*AM.dat* file). This kind of information will be very useful for the next computations.

4.5.1.1 Reconstruction of BSPs for *Vaughan – Ambrosio*'s model

After we have calculated the orientation matrices for all the limbs and the joints positions, it's possible to evaluate the *length* of the segments; this step is related just to the *Vaughan – Ambrosio*'s model, since in Dumas model we measure directly the segments lengths on the subject and we don't need so to scale BSPs according to the joints position.

The segments length file (*rl.dat*) contains the lengths evaluated like positions of distal joint in relative coordinates. It is so possible to reconstruct the BSPs yet calculated before scaling values obtained with Vaughan's and Ambrosio's models and defined before (see section 4.4.1).

4.5.1.2 Velocity and Acceleration

Once we have obtained Markers, Joints and Centres of Mass (CM) (stored in the *CM.dat* file) position along time, we can calculate their *Velocities* and *Accelerations* recurring to the *Central difference formulae*, which express velocity and acceleration of a *x* series like the first and second derivatives:

$$\frac{dx_n}{dt} = \dot{x}_n = \frac{x_{n+1} - x_{n-1}}{2\Delta t} \tag{4.5}$$

$$\frac{d^2 x_n}{dt^2} = \ddot{x}_n = \frac{x_{n+1} - 2x_n + x_{n-1}}{(\Delta t)^2} \tag{4.6}$$

where *n* refers to the *n*th sample frame and *Δt* is the time between adjacent frames, evaluated like the inverse of the sample frequency [Vaughan *et al.*, 1992]. This Finite difference method is derived from Taylor series expansions [Miller & Nelson, 1973].

4.5.2 Angular Kinematics

In this phase we calculate the *Anatomical Joint Angles* (relative angles) and the *Segment Euler Angles* (absolute angles). The Anatomical Joint Angles are needed to express the orientation of one segment relative to another; they are important in medical field, describing ranges of movement of clinical interest (e.g., hip abduction and adduction, knee flexion and extension, ankle inversion and subversion). The Segment Euler Angles define how one segment is orientated relative to the fixed global reference frame; we need them to calculate the angular velocities and angular accelerations of the segments, used in the equations of motion to calculate the joint moments [Vaughan *et al.*, 1992].

For both Anatomical Joint Angles and Segment Euler Angles, and all the related parameters, we operate just in computing values for the lower part of the body, following Vaughan *et al.* (1992) standards.

4.5.2.1 Anatomical Joint Angles

Vaughan *et al.* (1992) considered the segment reference reported in the following figure (*Figure 4-7*), in which each joint has a reference frame in the proximal and distal segments. A *Joint angle* is the rotation of the distal segment relatively to the proximal segment. The rotations are so defined:

• *flexion* and *extension* rotations, about the mediolateral axis of the proximal segment (i.e., the z axis in *Figure 4-7*).;

• *internal* and *external*, about the longitudinal axis of the distal segment (i.e., the x axis in *Figure 4-7*).

• *abduction* and *adduction*, about a floating axis that is at right angles to both the flexion/extension and internal/external rotation axis [Vaughan *et al.*, 1992].

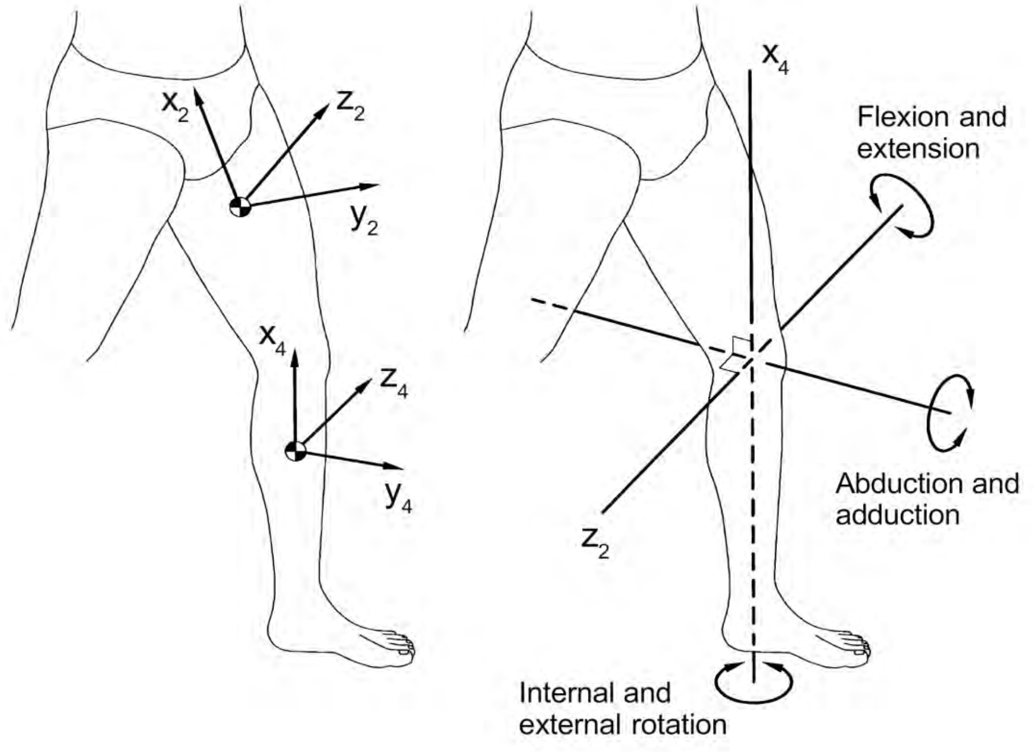


Figure 4-8. The segment reference frames ($x_i y_i z_i$) placed at the centres of mass of each segment. Note the segment numbering system: 1, right thigh; 2, left thigh; 3, right calf; 4, left calf; 5, right foot; and 6, left foot. Refer to the text for the definition of these reference frames (Vaughan *et al.*, 1992).

To define the Anatomical Joint Angles we need to define a triad of axis to be applied to each segment of the lower part of the body in relation to the proximal/distal joint:

$\mathbf{k}_{\mathbf{Proximal}}$ = flexion/extension axis;

$\mathbf{i}_{\mathbf{Distal}}$ = internal/external rotation axis;

$\mathbf{l}_{\mathbf{Joint}}$ = flexion/extension axis,

where $\mathbf{l}_{\mathbf{joint}}$ is obtained like vectorial normalized product of $\mathbf{k}_{\mathbf{Proximal}}$ and $\mathbf{i}_{\mathbf{Distal}}$. The three angles of interest (α flexion/extension angle, β abduction/adduction angle and γ internal/external rotation angle), for each joints, are obtained starting by these local axis, following the standard reported in Vaughan *et al.* (1992) book; the Anatomical Joint Angles are saved in the *AJA.dat* file.

Finally we evaluate the *Anatomical Joints angular Velocities* just by differentiate the obtained data, like we do with Joints, Markers and CM displacement (*Central difference formulae*, Chapter 4.5.1.2).

4.5.2.2 Segment Euler Angle

Segment Euler Angles are fundamental in calculating segment angular velocities and accelerations. Since each segment (or free body) in 3D space has six degrees of freedom, we need six independent coordinates in order to define the segment's position: the three Centre of Mass' (CM) position coordinates *X*, *Y* and *Z* for each segment and the three *Euler angles*' coordinates [Vaughan *et al.*, 1992]. They consist of three rotations around a common point (the segment's CM), moved in a way to make it coincide with the origin of the global reference system xyz. We have to define a *line of nodes*, or rather a line making a right angles with both the global reference axis *Z* and the segment axis *z*. Finally, we rotate the local segment *xyz* system from the *XYZ* (global) system to its actual position, performing the three rotations in order (*Figure 4-8*):

- ϕ about the Z axis;
- θ about the lines of nodes;
- ψ about the z axis [Vaughan *et al.*, 1992].

Here we used the particular convention adopted by Synge and Griffith (1959) and Goldstein (1965).

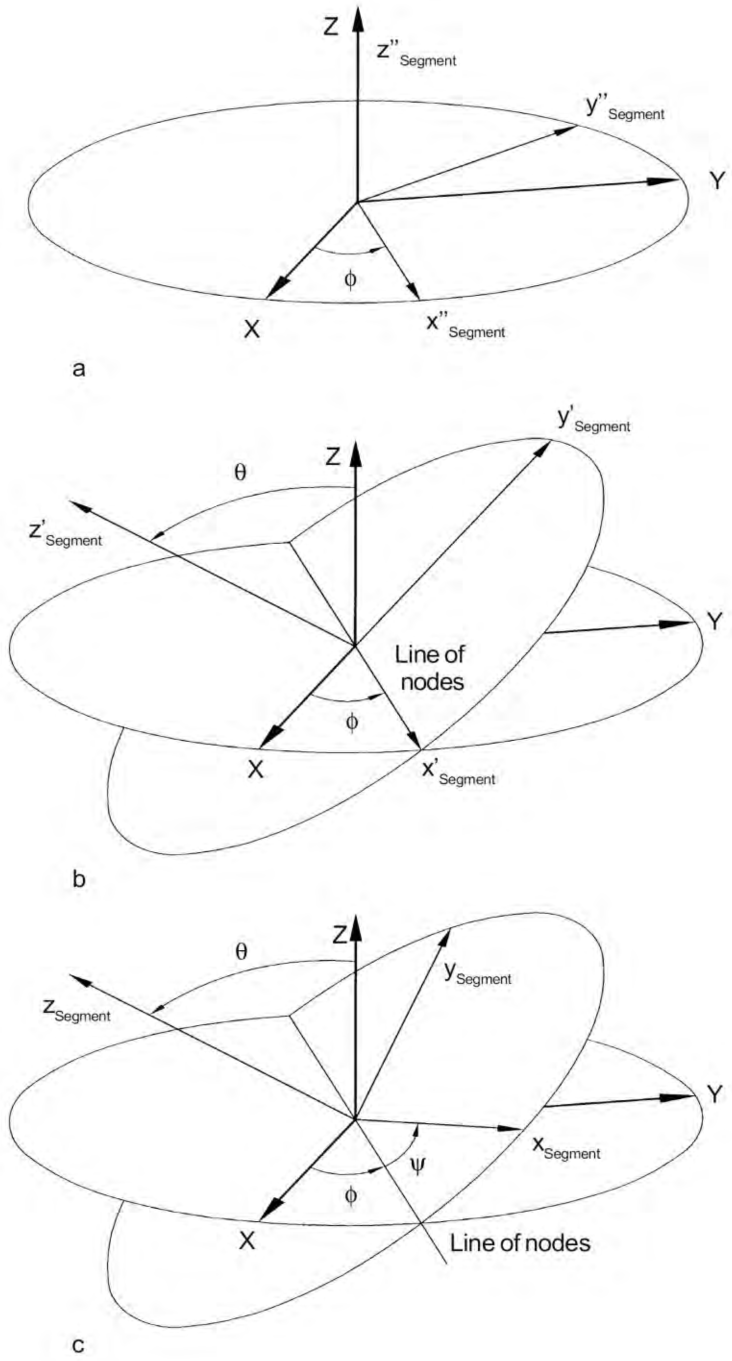


Figure 4-9. The three angular degrees of freedom (or Euler angles $\phi_{Segment}$, $\theta_{Segment}$, $\psi_{Segment}$) defining the orientation of a segment's reference axis ($x_{Segment}$, $y_{Segment}$, $z_{Segment}$) relative to the global reference system XYZ (see Goldstein, 1965). Note that the CM has been moved to coincide with the origin of XYZ. The three Euler angle rotations take place in the following order: (a) $\phi_{Segment}$ about the Z axis; (b) $\theta_{Segment}$ about the line of nodes; and (c) $\psi_{Segment}$ about the $z_{Segment}$ axis. The line of nodes is perpendicular to both the Z and $z_{Segment}$ axis. The primes and double primes indicate the intermediate axis positions [Vaughan *et al.*, 1992].

4.5.2.3 Angular Velocity and Acceleration

Once we have calculated the Euler Angles for each segment along time, we can obtain *angular velocities* (*SDvel.dat* file) and *accelerations* (*SDacc.dat* file) as functions of Euler Angles and their first and second derivates.

The *segment angular velocity* (ω) components may be obtained from the Euler angles as follows:

$$\omega_{\text{segment,x}} = \dot{\phi}\sin\theta\sin\psi + \dot{\theta}\cos\psi \tag{4.7}$$

$$\omega_{\text{segment,y}} = \dot{\phi}\sin\theta\cos\psi - \dot{\theta}\sin\psi \tag{4.8}$$

$$\omega_{\text{segment,z}} = \dot{\phi}\cos\theta + \dot{\psi} \tag{4.9}$$

where the ω is relative to the global coordinate system and its reported components are the projections to the local reference frame $x_i y_i z_i$.

Similarly, the *segment angular acceleration* ($\dot{\omega}$) components, or rather its projections to local coordinate system, are calculated as follows:

$$\dot{\omega}_{\text{segment,x}} = \ddot{\phi}\sin\theta\sin\psi + \dot{\phi}\dot{\theta}\cos\theta\sin\psi + \dot{\phi}\dot{\psi}\sin\theta\cos\psi + \ddot{\theta}\cos\psi - \dot{\theta}\dot{\psi}\sin\psi \tag{4.10}$$

$$\dot{\omega}_{\text{segment,y}} = \ddot{\phi}\sin\theta\cos\psi + \dot{\phi}\dot{\theta}\cos\theta\cos\psi - \dot{\phi}\dot{\psi}\sin\theta\sin\psi - \ddot{\theta}\sin\psi - \dot{\theta}\dot{\psi}\cos\psi \tag{4.11}$$

$$\dot{\omega}_{\text{segment,z}} = \ddot{\phi}\cos\theta - \dot{\phi}\dot{\theta}\sin\theta + \ddot{\psi} \tag{4.12}$$

4.6 Force plate measurements analysis

The Force plate measurements directly provided by the software used for the *force plate* capture; this kind of data, as said before, is stored in two files: *FPL1.txt* and *FPL2.txt*, related respectively to the first and the second force plate. Since the Force and Torque values are reported in the course of time and considering that the subject performing the gait passes firstly on the first force plate and then on the second, we can consider the global force data like the sum of the values stored in the two files, since these are measured both during all the performance duration. The Torque values are about the axis passing through the centre of the plate.

Each force plate provides six pieces of information:

- Force in X direction, F_X
- Force in Y direction, F_Y
- Force in Z direction, F_Z
- Torque about X axis, T_X
- Torque about Y axis, T_Y
- Torque about Z axis, T_Z

4.7 Evaluation of the *Centre of Pressure* (*COP*)

Once we have obtained the Forces and Torques components, it's possible to evaluate the values of the *Centre Of Pressure* (*COP*) coordinates along time. To define this point, consider, while performing the gait, one single foot in contact with the ground. The pressure forces, normal to the sole, could be considered in a single resultant force, exerted at the point where the resultant moments T_x and T_y are zero, referring to the illustration below (*Figure 4-9*). This point is termed *COP* [Sardain & Bessonnet, 2004].

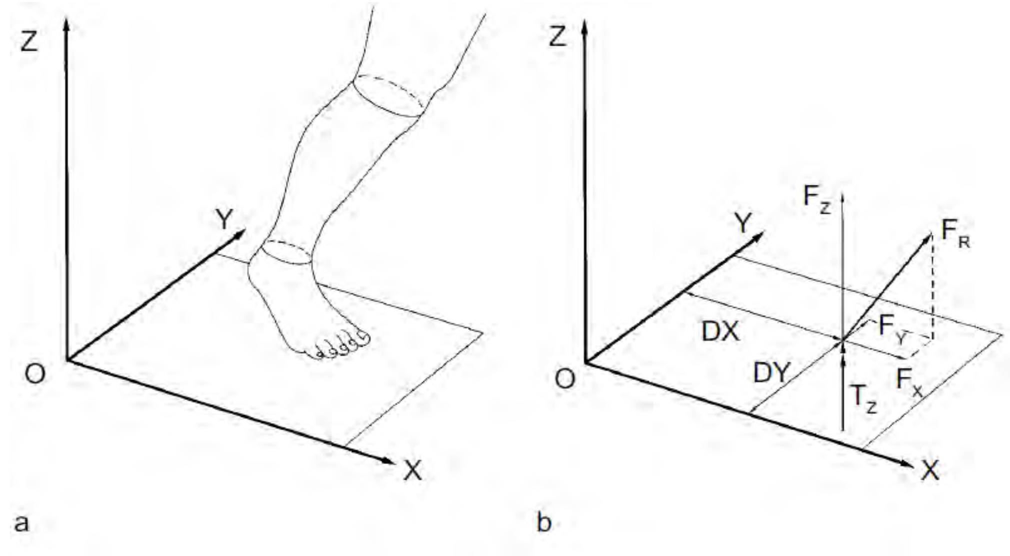


Figure 4-10. The force plate used to measure the reaction forces of the ground acting on a subject's foot: (a) view of foot and plate showing XYZ global reference frame; (b) the resultant force F_R of the plate on the foot has three orthogonal components- F_X, F_Y, and F_Z. The position of this resultant force is specified by the coordinates DX and DY, and TZ is the torque applied to the foot about the vertical Z axis [Vaughan *et al.*, 1992].

The COP is a 2-dimensional defined point, counting coordinates just on the floor plane (*X* and *Y*), since it is the point in which the reaction force by the floor is applied to the subject (so $Z = 0$). Considering the definition of COP, in particular the statement that the resultant moments about X and Y axis have to be zero, we can define the X (*DX*) and Y (*DY*) values of the COP position, referring to the picture above, applying the equilibrium on the torques about *X* and *Y*; the M_{DX} and M_{DY} have to be zero:

$$M_{DX} = T_X - F_Z \cdot DY = 0 \rightarrow DY = \frac{T_X}{F_Z} \tag{4.13}$$

$$M_{DY} = T_Y + F_Z \cdot DX = 0 \rightarrow DX = -\frac{T_Y}{F_Z} \tag{4.14}$$

Executing these operations for all the frames, it is possible to obtain the values of the COP during all the performance, stored in the *COP.dat* file.

An important application for the COP is in studying the *Stabilogram*, obtained like the measurement of the COP oscillations, plotting the COP's coordinates (*DX* and *DY*) together on the same plane. This kind of study is very common in both clinical and sport fields.

Another important clinical parameter consists in the difference between the projection of the *Total Body Centre of Mass* (*CM*) on the floor (Z = 0) and the *COP*. With our GUI it is possible to observe this parameter (under the voice “CM - COP”).

CHAPTER 5

GRAPHICAL USER INTERFACE ENVIRONMENT: THE *GUI_PROJECT*

The aim of this work is the creation of a GUI that allows the user to process both kinematical and force plate measurements starting directly by the data provided by the capture software. In this section, we will explain how the GUI works, describing, step by step, the functioning of every single tool and tracking the way to be followed for the execution of the complete data analysis with the created device, called *GUI_project*.

In the next sections, we will repeatedly report the term “process”: with this expression we refer to all the procedure that the user follows, starting by the kinematic and the force plates' data until the end of the processing, going behind all the steps that we will report step by step in this chapter. Finally, the user will be able to access to the created process, by assigning to it a specific name at the end of the processing phase.

Figure 5-1. Main page of our GUI for Gait Analysis

5.1 Processing of a new set of data

In this phase it will be shown how to start from *.c3d* (kinematical data) and *.txt* (force plate data) files, executing on them all the procedures that we have exposed in *Chapter 4*. The first step is the opening of the main GUI's interface (*Figure 5-1*), clicking on the *Matlab Figure* file named *GUI_project* (*Figure 5-2*).

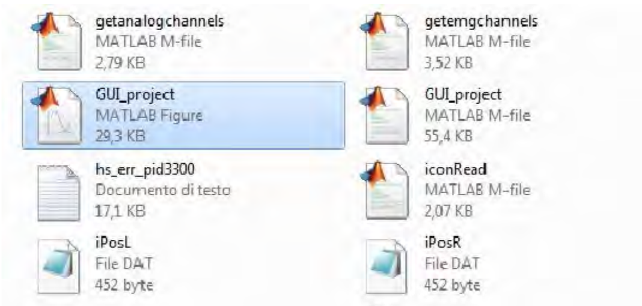


Figure 5-2. Launching GUI icon – GUI_project

This operation will open the main page of the GUI (*Figure 5-3*); in order to process a new data set, the user has to click on ―New file”, that is the first button on the left side of the toolbar, and then answer ―Yes” in the question dialog box that will be automatically opened; you can select ―No” if you want to remain on the main page.

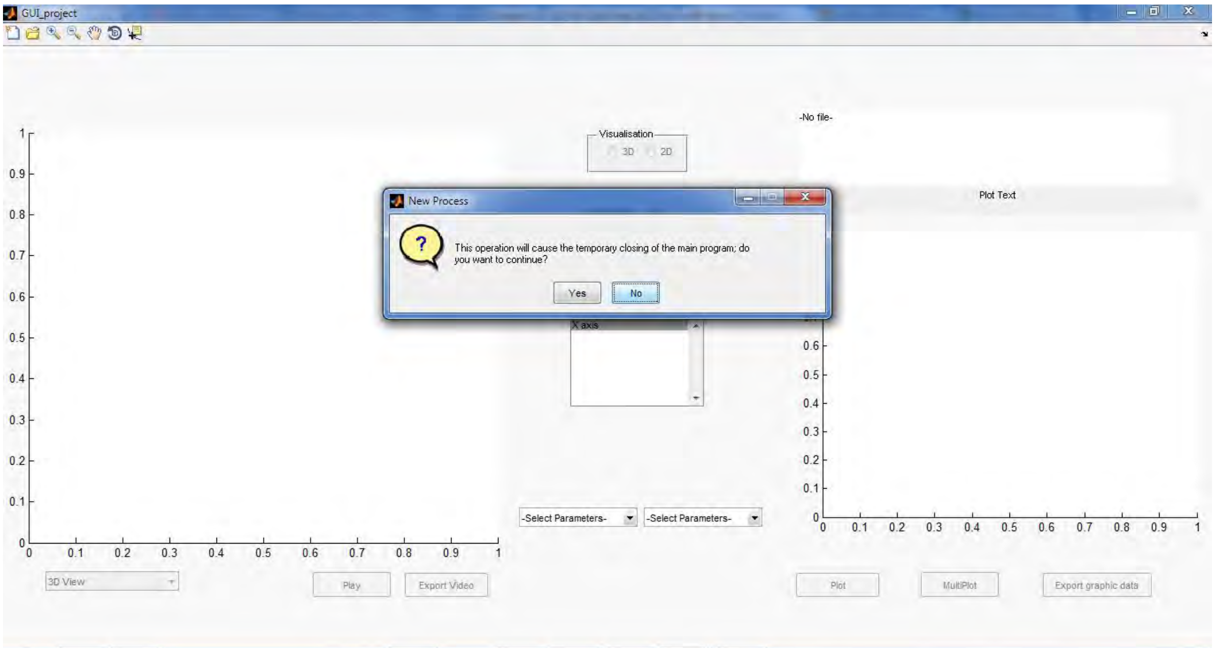


Figure 5-3. Picture showing the question dialog box – *New file*

At this point, the main page will be momentarily closed while a new interface, named *Process Creation*, is open (*Figure 5-4*). The first step here is the *Data selection* (*Figure 5-5*); the user has to select the kinematic data file (*.c3d*) and the force plates data (*.txt*), clicking respectively on *Capture data* and *Force plate data* (*Figure 5-5*). This allows the selection of the two files even if they are not stored in the same folder: in fact the created Matlab routine works in a way to make a copy of the *.txt* file in the same folder in which the kinematical file is stored.

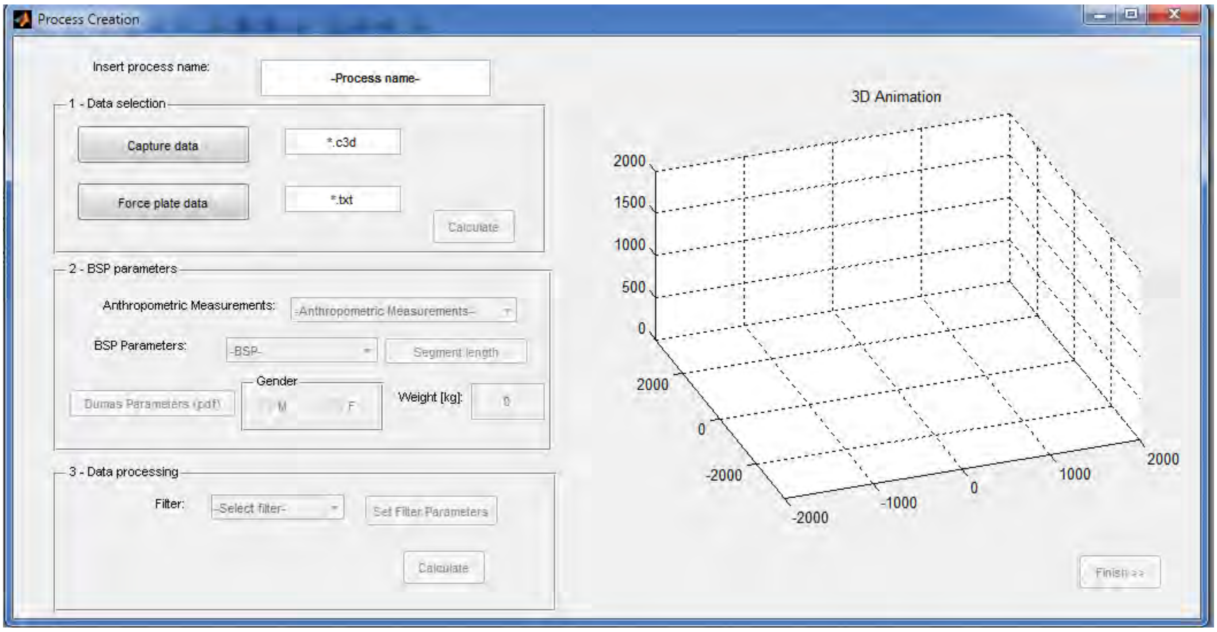


Figure 5-4. ***Process Creation*** **interface**

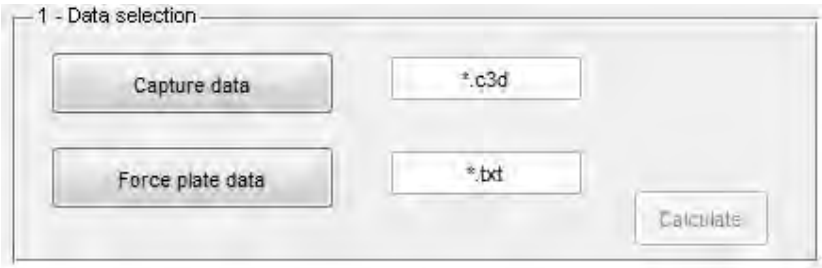


Figure 5-5. Starting ***Data selection***

Since the user has selected the two files, the routine enables the button –Calculate” in the same section (*Data selection*); this command executes the first step described in the previous chapter (*4.1* and *4.2*): the corrected markers are established and the Markers Trajectories are rebuilt as the Time array. Finally, the 3D video showing markers along time is represented in the right side of the *Process Creation* interface (*Figure 5-6*).

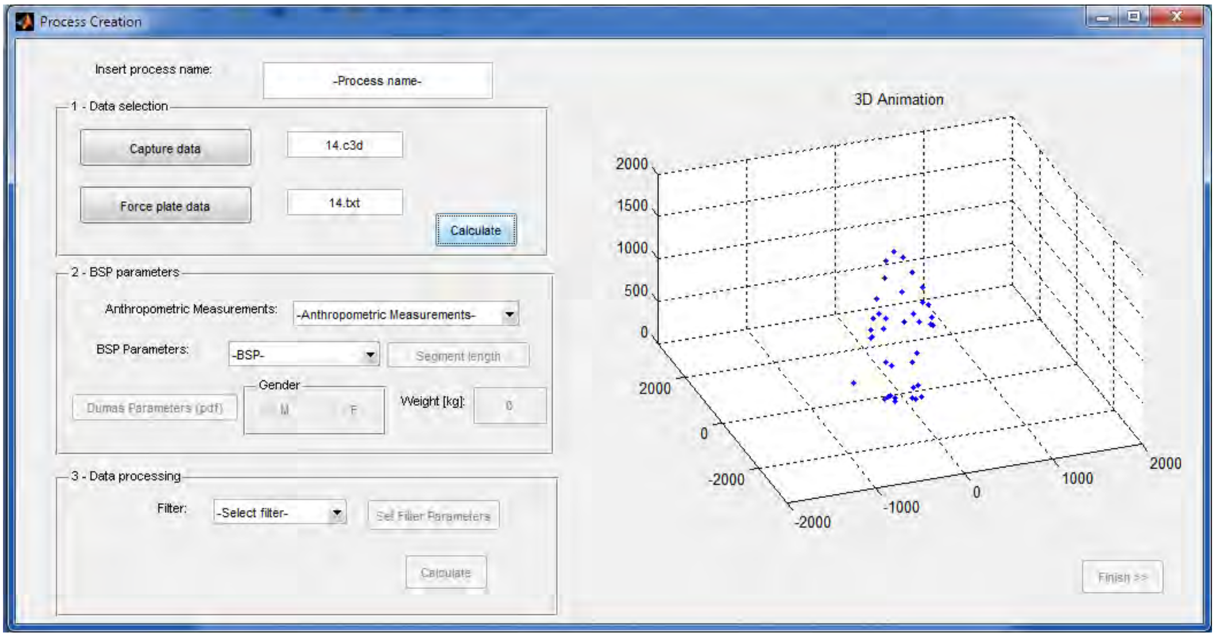


Figure 5-6. The *Process creation* interface performing the 3D markers video after the “Data selection”

Once the execution of the video is complete, the other two parts of the *Process Creation* interface are automatically enabled: the –BSP parameters” section and the –Data processing” one. In the *BSP parameters* section, under the voice –Anthropometric measurements”, the GUI will show a list in which the user can choose the anthropometric values among a set made of –Vaughan Normal Male”, –Vaughan Normal Female” and a set of measurements taken on a male subject in Lab (–Lab normal male”), as reported in the picture below (*Figure 5-7*).

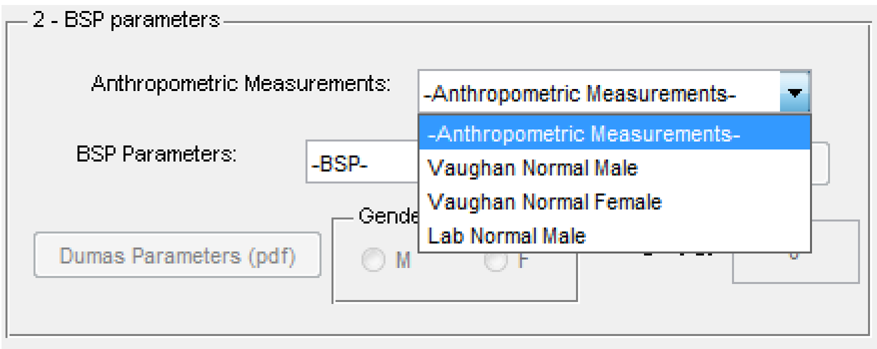


Figure 5-7. Anthropometric measurements choice list

As shown in the previous chapter, our GUI allows the selection between *Vaughan – Ambrosio*'s and *Dumas*'s BSP parameters. Selecting the *Vaughan – Ambrosio*'s parameters, it is not required to insert other BSP parameters, since they are all obtained by the anthropometric measurements, set before.

If the user selects the *Dumas*' BSP parameters, it is needed to insert other information like the segments' lengths, the gender of the subject and his weight (*Figure 5-8*). Clicking on ―Segment length", a box containing nine free spaces, related to the number of limbs in *Dumas*' model (considering symmetry for the total body), will be opened (*Figure 5-9*).

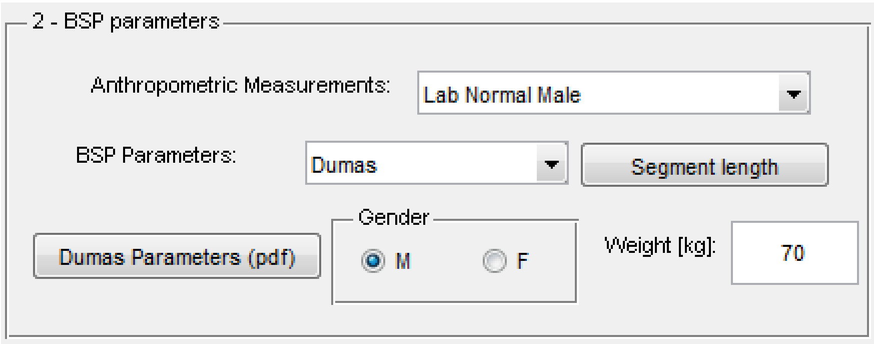


Figure 5-8. Example of Dumas' BSP data selection for a Normal Male, 70 kg weighted subject

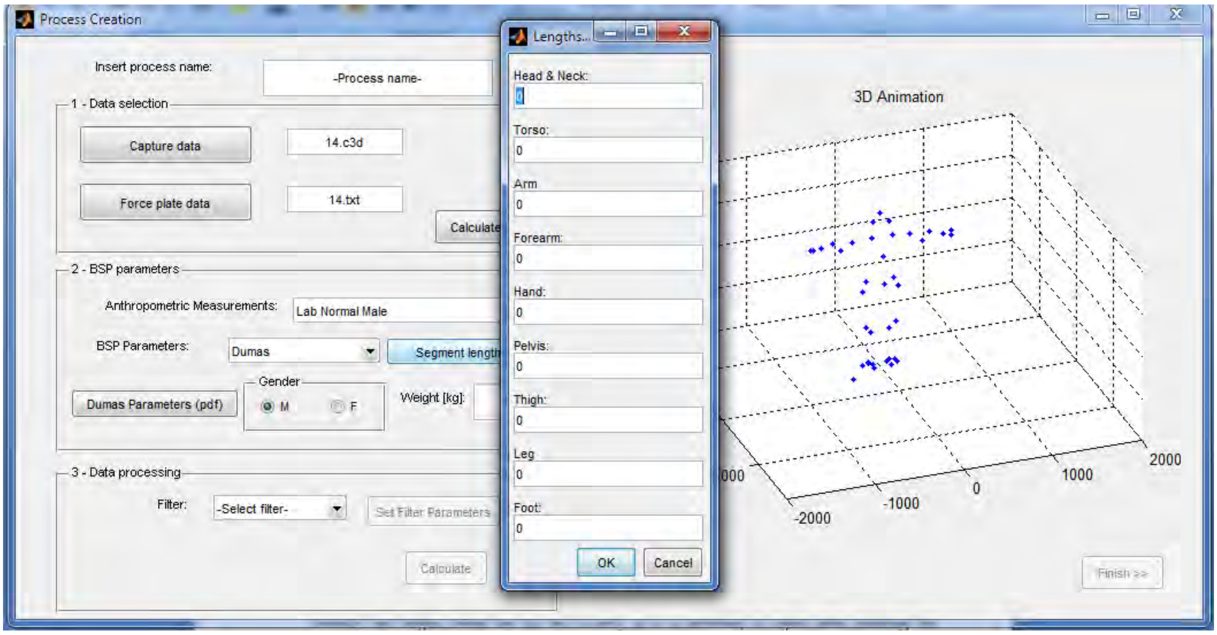
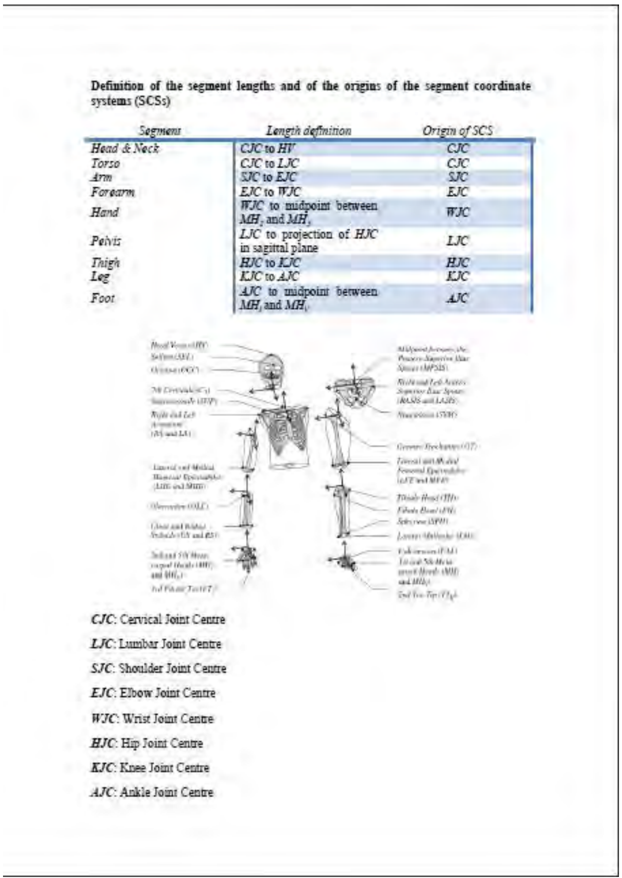


Figure 5-9. Segments' lengths box – *Dumas* BSP model

Initially the lengths' values are all set to zero, so it is necessary to input them inserting the values directly taken on the subject. Clicking on ―Dumas Parameters (pdf)" a window containing instructions in a *pdf* file, explaining how to make the segments measurements, is opened (*Figure 5-10*); this file contains also the links related to the used reference documents [Dumas *et al.*, 2007a], in order to provide a better explanation about the definition of the anatomical points defining the segments' length.



Definition of the segment lengths and of the origins of the segment coordinate systems (SCSs)

Segment	*Length definition*	*Origin of SCS*
Head & Neck	*CJC* to *HV*	*CJC*
Torso	*CJC* to *LJC*	*CJC*
Arm	*SJC* to *EJC*	*SJC*
Forearm	*EJC* to *WJC*	*EJC*
Hand	*WJC* to midpoint between MH_2 and MH_5	*WJC*
Pelvis	*LJC* to projection of *HJC* in sagittal plane	*LJC*
Thigh	*HJC* to *KJC*	*HJC*
Leg	*KJC* to *AJC*	*KJC*
Foot	*AJC* to midpoint between MH_1 and MH_5	*AJC*

CJC: Cervical Joint Centre
LJC: Lumbar Joint Centre
SJC: Shoulder Joint Centre
EJC: Elbow Joint Centre
WJC: Wrist Joint Centre
HJC: Hip Joint Centre
KJC: Knee Joint Centre
AJC: Ankle Joint Centre

Figure 5-10. Length definition for the *Dumas*' BSP model

The next step is the selection of the filtering technique, in the *Data processing* section; the user can select between *SSA* (*Singular Spectrum Analysis*) and a *Butterworth filter*. For the SSA technique the user can set the *length* of the *window* to be applied to the signal pushing the ―Set Filter Parameters" button (*Figure 5-11*); the default window length value is 10. For the Butterworth filter, clicking on the same button, it is possible to select the *order* of the filter and both the *sample* and the *cutting frequencies*, in Hertz (Hz) (*Figure 5-12*). The cutting frequency has to be lower than the half of the sample one, otherwise the Matlab routine will indicate an error. By default, the Butterworth filter order is set to 2 while sample frequency value is 100 Hz (the camera's capture frequency) with a cutting frequency set to 10 Hz.

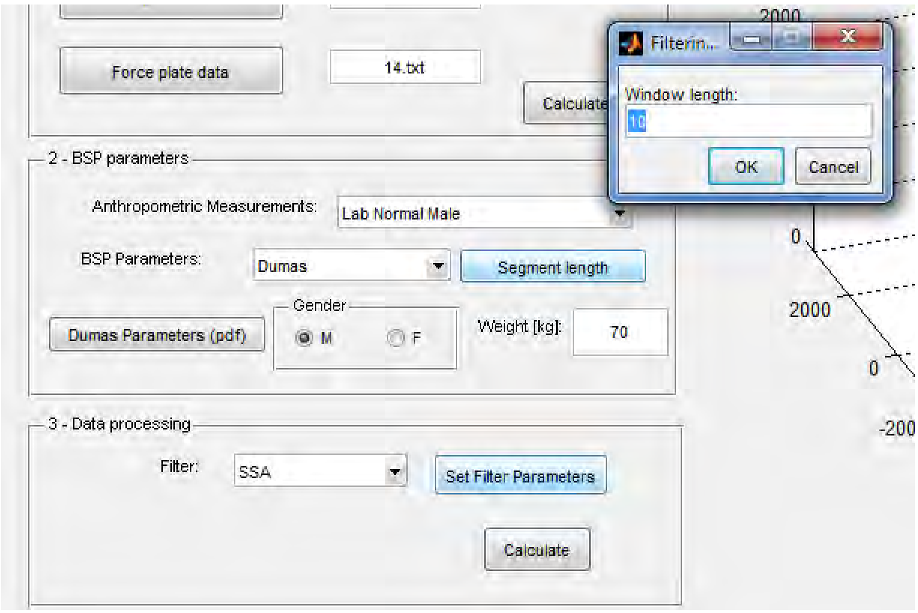


Figure 5-11. ***SSA*** **filtering technique – Window length definition**

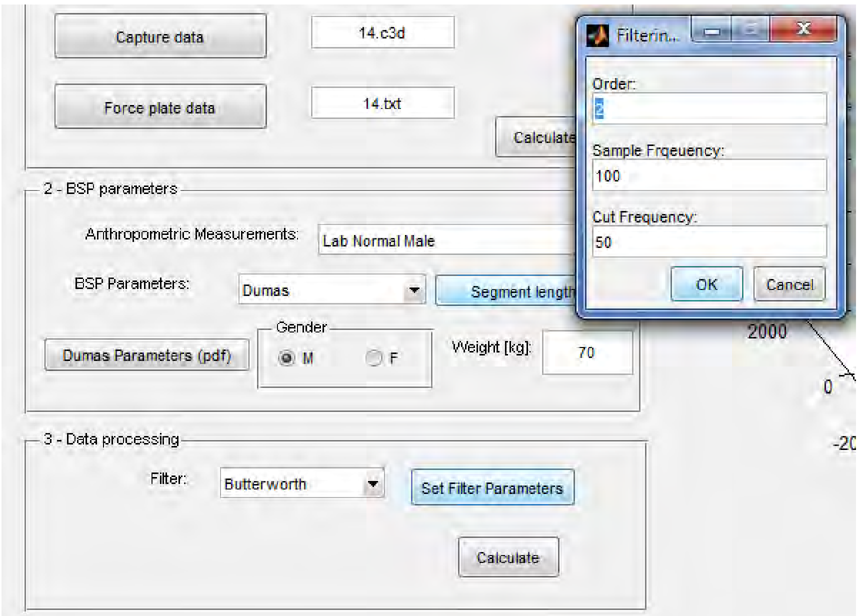


Figure 5-12. Butterworth filter – Parameters selection

After the user has defined the BSP parameters and the filtering technique features, the button ―Calculate" in the *Data processing* section is enabled. Pushing this button, a sequence of operations is performed (see *Chapter 4* for more detailed information):

- The kinematical data contained in the *.mat* file, related to the markers trajectories, is synchronized with the force plate file (*.txt*); an *output* subfolder is created in the same folder of the kinematical capture file, in order to store all the needed output files; as result of the synchronization, the *rm.dat*, with the markers trajectories along time, and the *FPL1.dat* and the *FPL2.dat* files, containing the force plate information along time provided respectively by the first and the second force plate, are created and stored in the output folder;
- The trajectories data contained in the *rm.dat* file is filtered, using the filter selected by the user;
- The BSP model, selected by the user, is applied to the kinematical data, in order to evaluate the segments' masses, their moments of inertia and their CMs (Centres of Mass). In the case of *Vaughan – Ambrosio*'s model the BSP parameters are reconstructed recurring to the kinematical data;
- Starting by the markers trajectories, the positions of the joints along time, in the absolute coordinate system, are rebuilt, as the orientation of the segments along time;
- The angular kinematics is totally defined, calculating the *Anatomical Joint Angles* and the *Segment Euler Angles* and obtaining then the angular velocities and accelerations for each segment of the lower body;
- Starting by the kinetics data in the *FPL1.dat* and *FPL2.dat* files, the position of the *COP* (*Centre of Pressure*) along time is calculated.

This series of operations could require several seconds; once everything is done, the user has to assure himself that the process executed has been renamed, inserting a new name in the upper left part of the interface (*Figure 5-13*) and then push the button ―Finish" in the lower right part. The *Process Creation* interface will be so closed and the main GUI interface (*GUI_project*, *Figure 5-1*) will be opened again, in order to operate on the saved process.

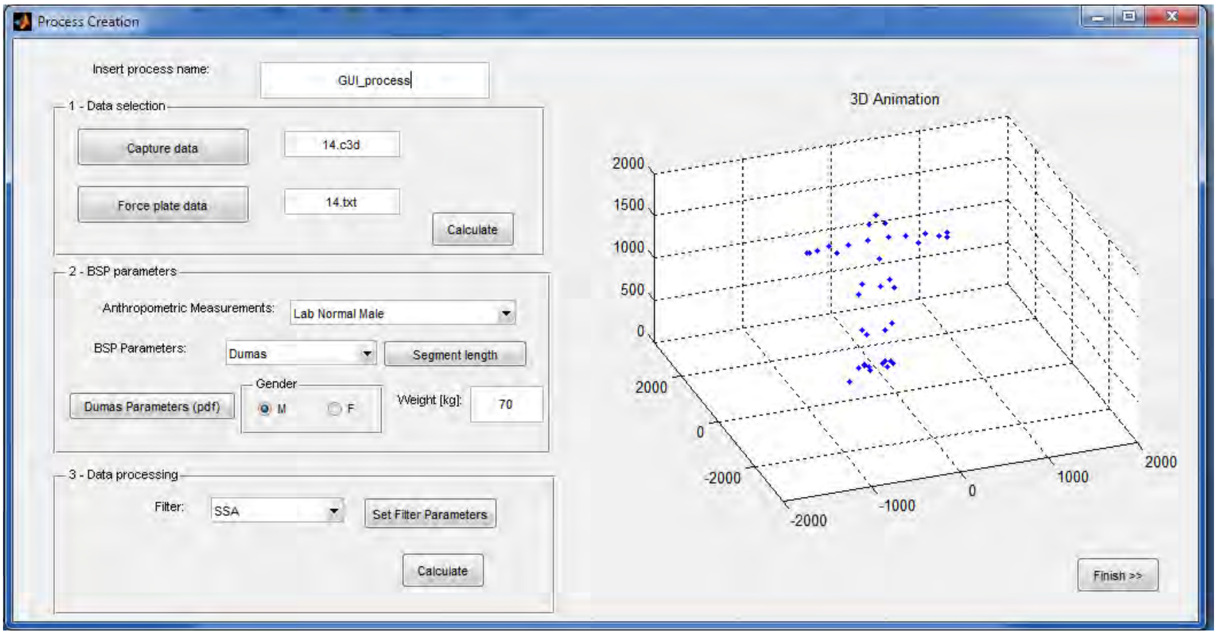


Figure 5-13. Final configuration for the *Process Creation* interface

At the end of the data elaboration, the user can find a folder, the same of the kinematical *.c3d* starting data, containing the following objects:

- The *.c3d* file;
- The *.txt* force plate file, named as the *.c3d* file;
- The *.mat* file created after the *Data selection* section;
- The Anthropometric measurements file (*APMm.dat* for the ―Vaughan normal male”, *APMf.dat* for the ―Vaughan normal female” and *APM.dat* for the ―Lab normal male”);
- A file containing correction based on densitometry, if present, and actually provided just for the ―Lab normal male” (*DXA.dat*); this kind of data is used to obtain correction on the calculation of the lower body part segments’ inertial parameters;
- A *.dat* file, named with the process name selected by the user (―Insert process name”, as described before); this file contains on the first line the name of the folder in which all the process’ data is stored, on the second line the *Name* of the *.c3d* file (therefore the same of the *.txt* force plate and the *.mat*), on the third line the *Date* of the process creation, on the fourth line the *Sample frequency*, on the fifth line the *BSP model* used and on the last line the *Filtering* technique applied

(*Figure 5-14*). All this information is necessary in the main interface (*GUI_project*), as we will explain in the next section. In the reported example the process is named “GUI_process”, therefore the corresponding file is “GUI_process.dat”;

```
C:\Users\Marco\Desktop\prova\
File name:14
Date:2011-9-2 18:49:35
Sample frequency:100Hz
BSP model:Dumas
Filter:SSA
```

Figure 5-14. Contents of the *.dat* process file

- The *out* subfolder, containing all the useful output files, accounted in the following table (*Table 5-1*):

File Name	Description
rm.dat	Markers position along time
r0.dat	Joints position along time
rg.dat	Local position of the CM, referred to the proximal joint
rl.dat	Segment lengths (differently expressed for *Vaughan – Ambrosio* and *Dumas* models[7])
CM.dat	Centres of Mass position along time
AJA.dat	Anatomical Joint Angles for the lower body part along time
SDvel.dat	Angular velocity for each segment of the lower body part along time
SDacc.dat	Angular acceleration for each segment of the lower body part along time
AM.dat	Segments orientation along time
FPL1.dat	Reaction Forces and Torques along time provided by the first force plate
FPL2.dat	Reaction Forces and Torques along time provided by the second force plate

[7] For the *Vaughan – Ambrosio* model the length of each segment is expressed like position of distal joint in relative coordinates, while in *Dumas* model we report the lengths of the subject’s limbs directly measured; see the previous chapter (4.4) for more details.

COP.dat	Centre of pressure along time
mass.dat	Segments mass
MI.dat	Moments of inertia about the CM for each segment

Table 5-1. Contents of the *out* subfolder

5.2 Opening of an existing process

Once the user has processed a new set of data, creating a new process, he has to click on the second button on the upper left side of the main GUI (the *GUI_project* interface, *Figure 5-1*), the ―Open File” button (*Figure 5-14*); this will allows the user to select the desired process by choosing directly the process named *.dat* file from his folder (the ―GUI_process.dat”, in our case).

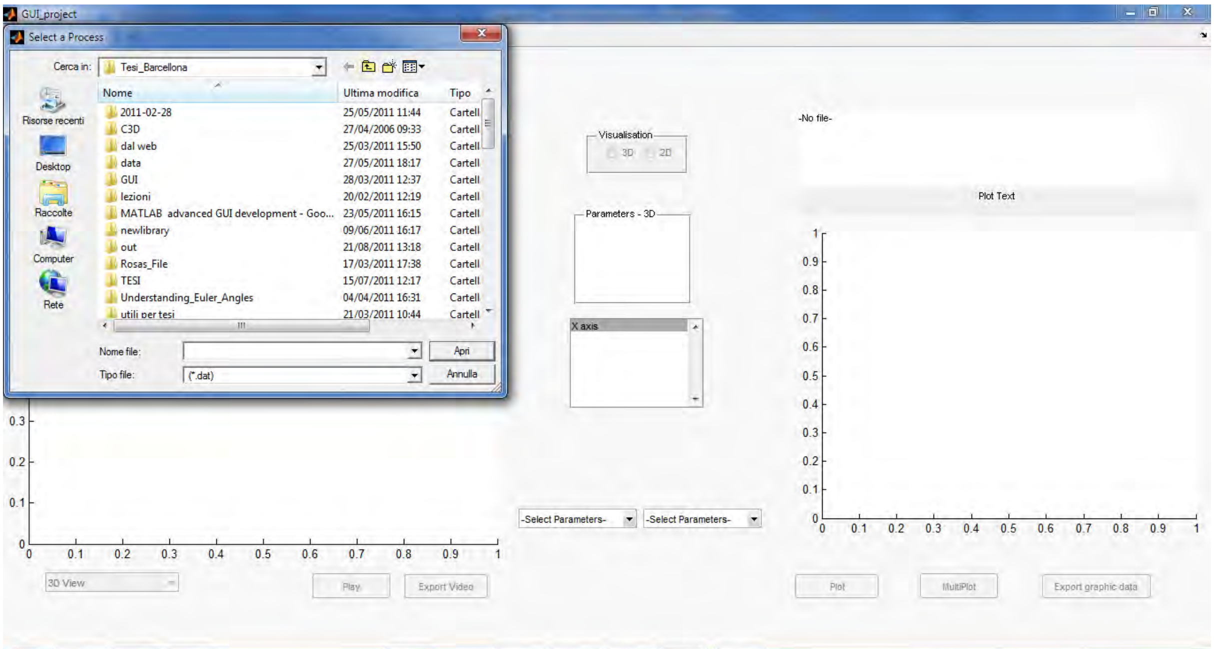


Figure 5-15. Process opening – GUI main interface

Since the *.dat* file is selected, the contents of the file (the same related in the *Figure 5-14*) are shown in the upper right part of the main interface (*Figure 5-15*), in a way to make all the information about the selected BSP parameters, the filtering technique used and the sample frequency, as well as the information about the process creation (date of creation, file name and storage folder) available to the user. The Matlab copies the *out* subfolder contained in the process storage folder (first line of “GUI_process.dat”) in the folder in which the GUI routine is stored: every time a different process is opened, the out subfolder contained in the GUI folder is replaced by the new one. After these operations, the process information is totally available. It is important to notice that the process (with all the related files) could be stored in the same folder of the GUI routine: rather, this could be better in terms of time processing and data reading.

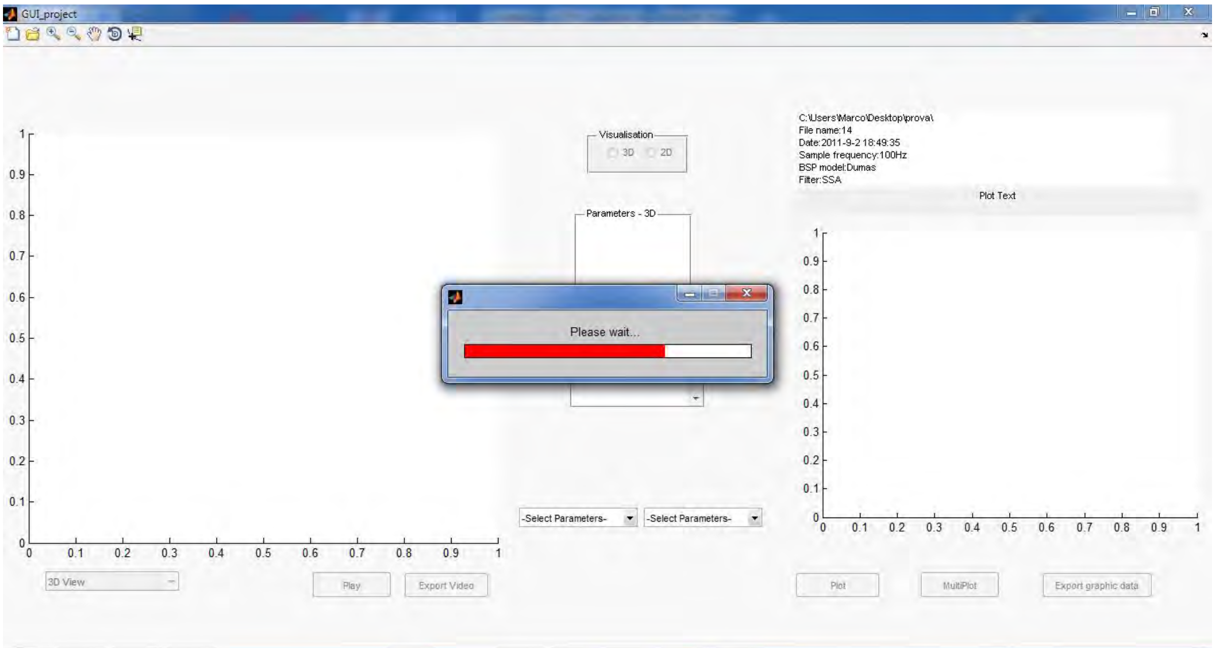


Figure 5-16. Process opening – GUI main interface

While copying the *out* folder content, the GUI will show an error box dialog in case the file is not found (*Figure 5-17*); this means that the information related with the lost file will not be available for the user (for example, if the *CM.dat* file is not available the user cannot visualize the Centres of mass positions, velocities and accelerations along time, neither the distance between the projection of the CM on the floor and the Centre of Pressure, *Figure 5-18*).

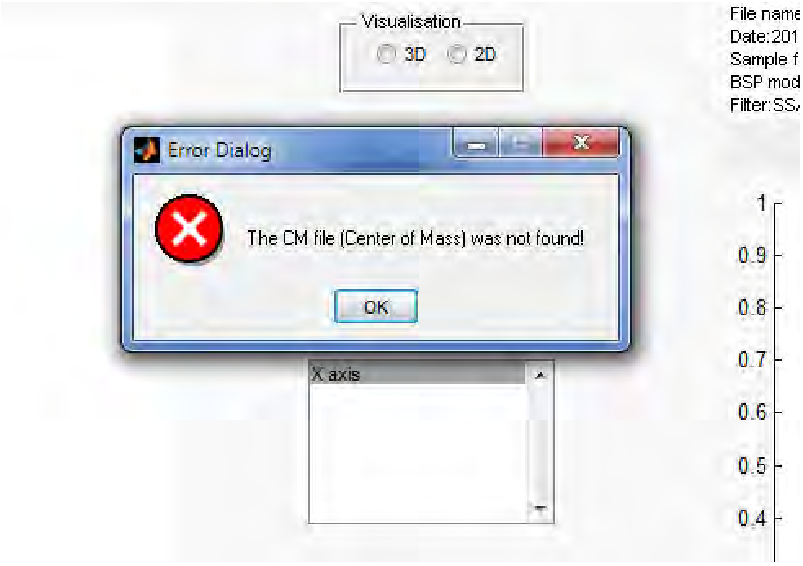


Figure 5-17. Example of Error routine in case of not found CM.dat file

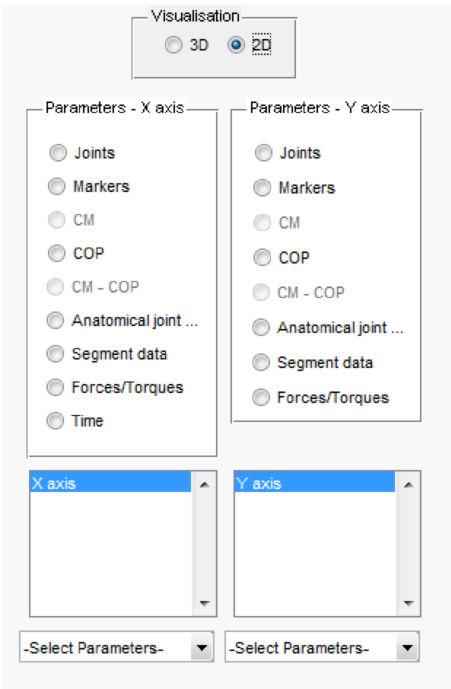


Figure 5-18. Example of not enabled CM and CM-COP parameters, because of the CM.dat file was not found

5.3 *GUI_project* functioning

In this section we will explain the functioning of every section and button reported in the main interface of our *GUI_project*. Since the process is opened, the user can access to all the process information contained in the *out* subfolder. The purpose of the developed GUI is that of making the user able to access to the process contents by a direct graphical way, selecting by a list the parameters to be plotted, with the opportunity of exporting them in a new file; furthermore, the user could be able to visualize a video of the recorded gait, reconstructed starting by the elaborated data and export it in *.avi* format.

5.3.1 Video settings

Our GUI allows the visualization of the video related to the gait performed by the subject in the axis on the left side of the interface; the reproduction of the action is made recurring to a 18 segments model, reporting markers (white balls), joints (gray balls) and, for each segment, the corresponding local axis system. The model is reconstructed starting by the kinematical data obtained in the previous steps. The gait reproduction shows also the force plates and the reaction forces, both in magnitude and direction (*Figure 5-19*).

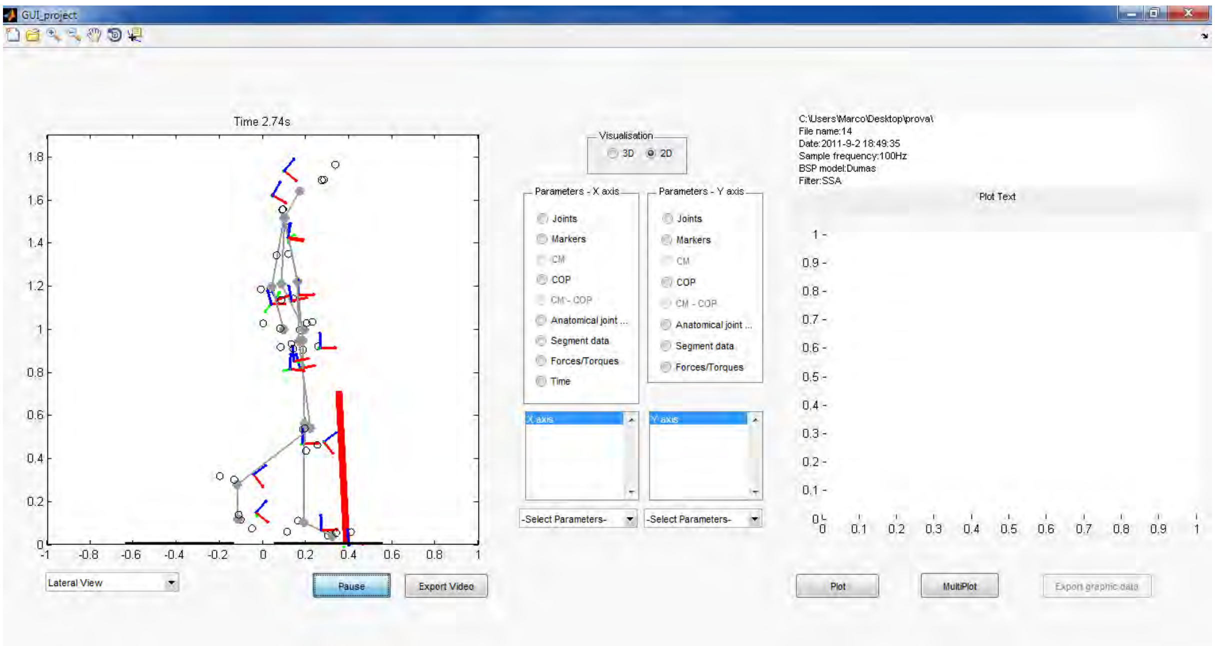


Figure 5-19. Example of the GUI while performing the Gait video – Lateral View

In order to start the reproduction of the video, the user can push the –Play/Pause” Toggle button. At the first launch, the button will not be pressed, showing the tag –Play”; by pushing it, it is possible to start the reproduction. This operation will turn the tag into –Pause”: in fact, pushing again, the reproduction can be temporarily stopped (*Figure 5-20*).

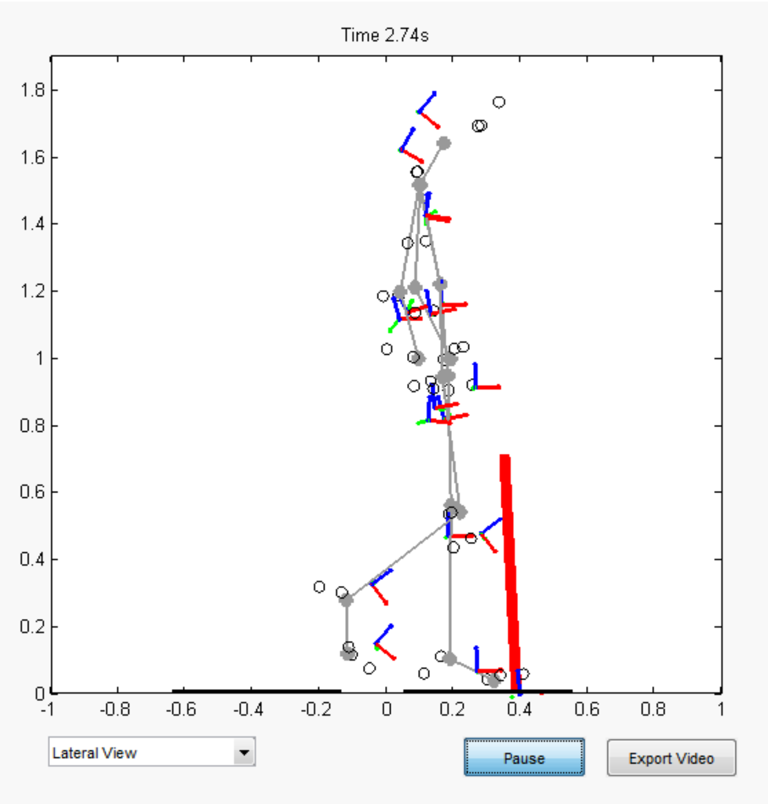


Figure 5-20. Video section with its tools: View list, Play/Pause and Export Video buttons – *GUI_project*

The –Export Video” (*Figure 5-20*) button allows the user to export the video in a 25 frame per second *.avi* format; the user can select the folder in which store the video by a window that is automatically opened. During the creation of the *.avi* file, the frames are reported on the computer display in a separated window: it is essential not to touch anything while this operation is running, in order not to compromise any frame of the new video file. Depending on the speed of the processor, this operation could take from few seconds to some minutes (*Figure 5-21*).

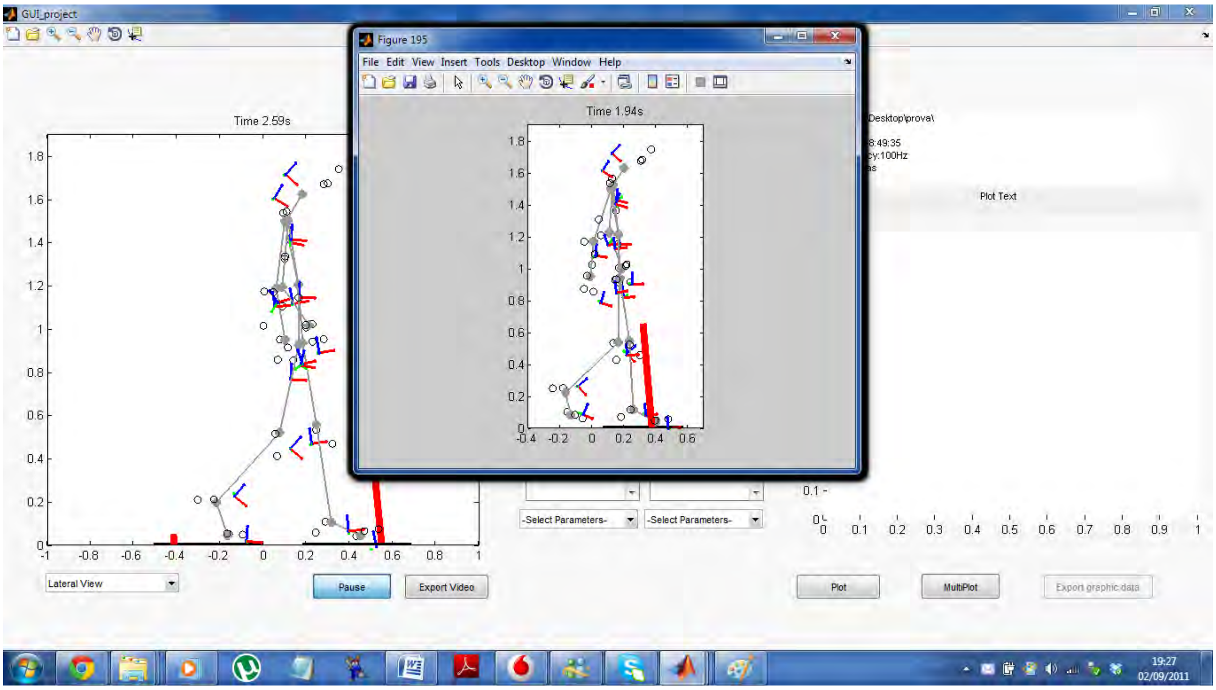


Figure 5-21. Exporting Video phase

Both for the video visualization and its export, the user can select among three different views reported in a list at the left of the ―Play/Pause" button; the ―3D view" shows the gait in a tri-dimensional space, the ―Lateral view" in the *xz* plane (Sagittal plane) and the ―Frontal view" in the *yz* plane (Frontal plane), as reported in the *Figures 5-22*, *5-23* and *5-24*.

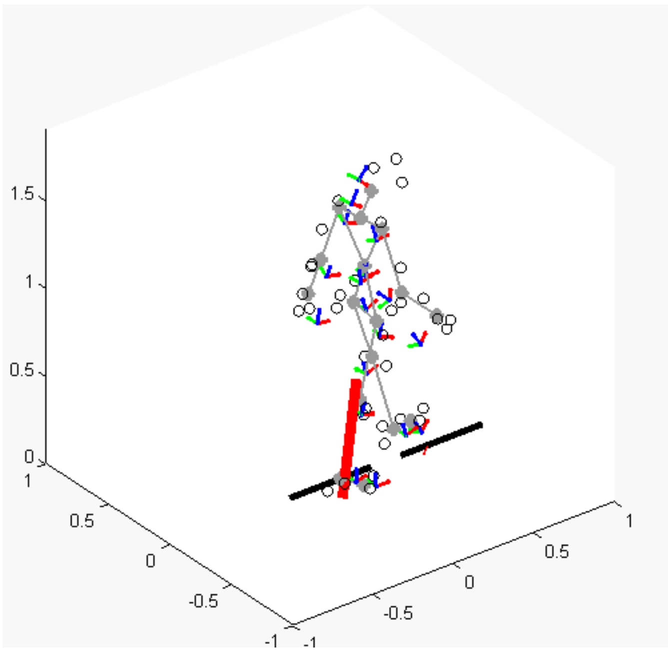


Figure 5-22. Video 3D View

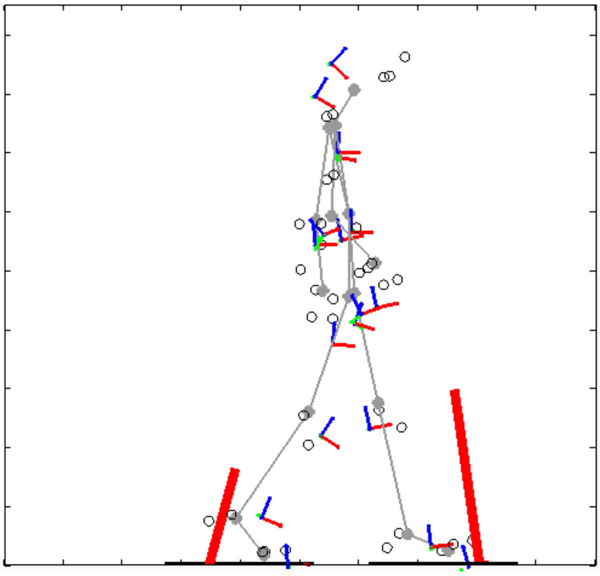


Figure 5-23. Video Lateral view

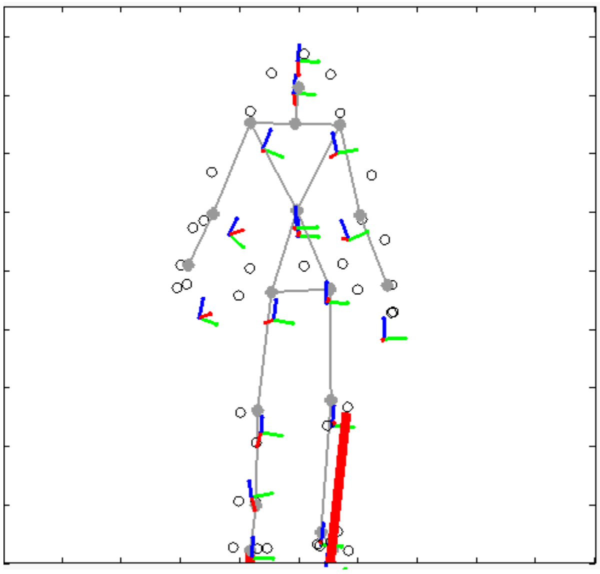


Figure 5-24. Video Frontal view

5.3.2 Plot settings

The created GUI allows the visualization of all the kinematical and force plate measurements obtained in the previous steps, both in *2-dimensional* and *3-dimensional* views. Once the user has selected the parameters to be plotted, described and reported in the following sections, it is possible to visualize them on the right side axis of the interface. This operation is performed just pushing the ―Plot" button, on the right side below the axis (*Figure 5-245* example of data plotting area).

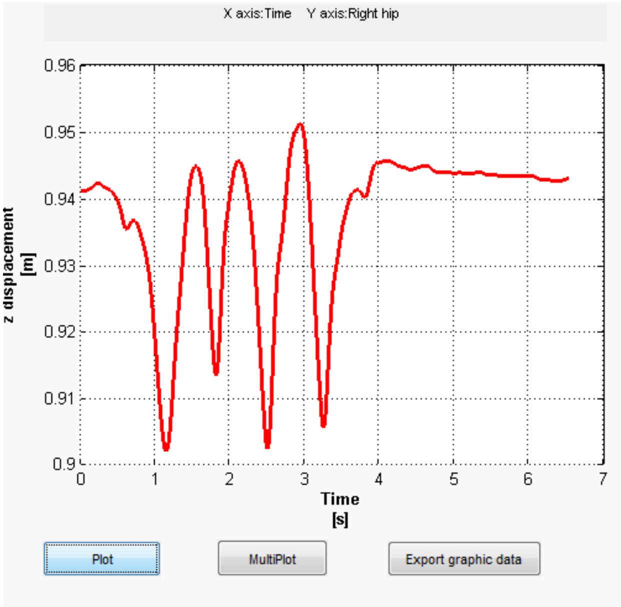


Figure 5-25. Example of data plotting are with Plot, MultiPlot and Export graphic data buttons, while plotting the Right Hip z component displacement along time

The ―Multiplot" button (*Figure 5-25*) allows the user to make a graphical comparison among two or more trajectories, plotted on the same graph with different colours; this kind of evaluation is possible just between similar physical sizes, so the user can choose to plot more trajectories just if they have the same dimensions along the axis (i.e., it is possible to plot together two Displacements in function of Time, having the same dimensions, length and time; it is denied to plot Force and Displacement on the same graph, since they have different dimensions). In the *Figure 5-26*, we report an example of multi-plotting.

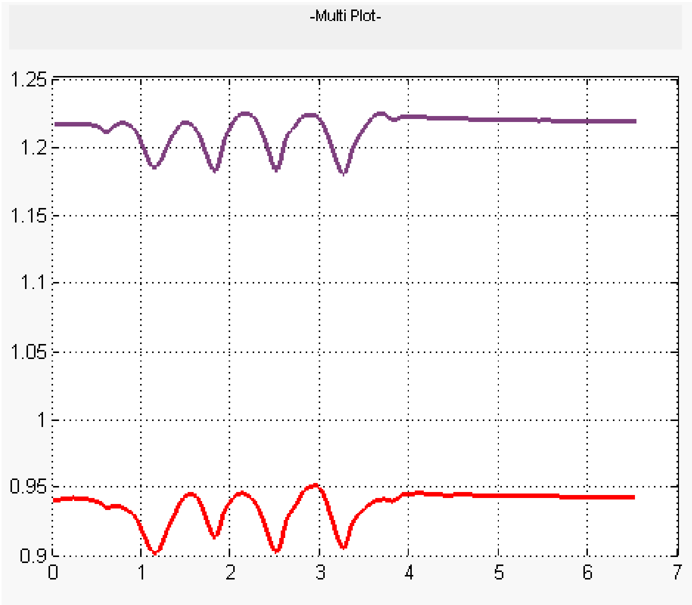


Figure 5-26. Example of multi-plotting data: Right Hip joint's (in red) and Lumbar joint's (in purple) z displacement along time

It is possible to export the visualized graphic data pressing the “Export graphic data” (*Figure 5-25*) button. The user can select, by a window automatically opened, the folder in which to save the new data file and the file format, among *.txt*, *.dat* and *.mat*.

The plotted parameters' labels are reported in the string above the Plotting axis, initially set to “Plot Text”; this is not valid in “MultiPlot” mode, in which the graph title is set to “-Multiplot-”. The dimensions are indeed reported among the axis of the graph, as reported in the previous examples (*Figure 5-25* and *5-26*).

Visualisation and *Check lists*

In the central part of the GUI the user can find the section “Visualisation”; in this section it is possible to select between 3-dimensional (*3D*) or 2-dimensional (*2D*) plotting. By selecting “3D” a *check list* of available parameters (“Parameters -3D”) will be opened; this list contains *Joints*, *Markers* and *CM* displacements, or rather the parameters related to physical points that move following trajectories in a 3-dimensional space. The selection of the “2D” mode, on the other hand, will allow the opening of two different *check lists*, the first one related with the *x axis* (“Parameters – X axis”) and the latter with the *y axis* (“Parameters – Y axis”) (*Figure 5-27* – example of parameters list for 2D Visualization mode). Both lists contain the following parameters: *Joints*, *Markers*, *CM*, *COP*, *CM – COP*, *Anatomical Joint Angles*, *Segment data* and *Forces/Torques*. Furthermore, the plot of each parameter as a function of the time is permitted by the *Time* choice in the “Parameter – X axis”[8].

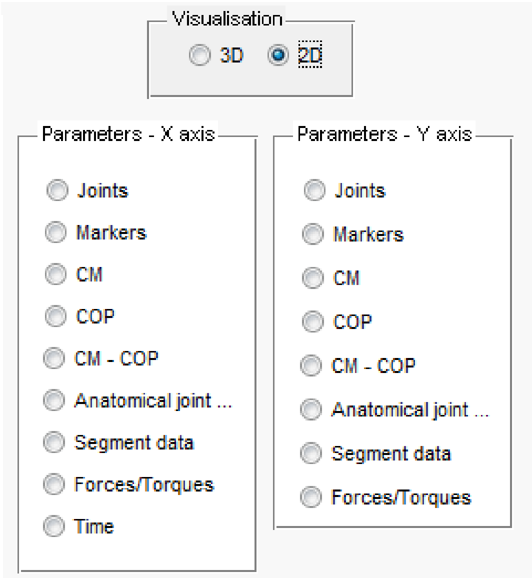


Figure 5-27. 2D plotting paramters

List boxes and *Pop-up menus*

The selection of the parameters of interest, by checking them in the previously described check lists, will change automatically the contents of the *List boxes* beneath the parameters check lists: depending by the chosen parameter, every *List box* will contain a set of the related specific components (i.e. the Joints and Markers list and the Segments list for the Centres of Mass parameter); we will report a full description in a summary table in the *Table 5-2*. Finally, the user can select the physical size to be plotted by the *Pop-up menus* beneath the list boxes; relatively to the “3D” visualization mode, as reported before, it makes sense to plot just the displacements along the three dimensions. The “2D” mode allows the selection of several physical components along the *X* and *Y* axis.

[8] Look to the previous chapter (*4*) for more detailed information about the meaning of every single parameters

Parameters	***List box***	***Pop-up menu (2D)***	***Pop-up menu (3D)***
Joints	1 - Lumbar joint 2 - Right hip 3 - Left hip 4 - Cervical joint 5 - Right shoulder 6 - Left shoulder 7 - Head base 8 - Right elbow 9 - Right wrist 10 - Left elbow 11 - Left wrist 12 - Right knee 13 - Right ankle 14 - Left knee 15 - Left ankle 16 - Right foot joint 17 - Left foot joint	-x displacement -y displacement -z displacement -x velocity -y velocity -z velocity -x acceleration -y acceleration -z acceleration	-x displacement -y displacement -z displacement
Markers	1 - External right foot 2 - Right heel 3 - Right ankle 4 - Right tibia 5 - External right knee 6 - Right thighbone head 7 - Right hip bone 8 - External left foot 9 - Left heel 10 - Left ankle 11 - Left tibia 12 - External left knee 13 - Left thighbone head 14 - Left hip bone 15 – Sacrum 16 - Right high shoulder	-x displacement -y displacement -z displacement -x velocity -y velocity -z velocity -x acceleration -y acceleration -z acceleration	-x displacement -y displacement -z displacement

	17 - Right lateral shoulder 18 - Right elbow 19 - Right forearm 20 - Right wrist 21 - Right hand knuckle 22 - Right index knuckle 23 - Left high shoulder 24 - Right lateral shoulder 25 - Left elbow 26 - Left forearm 27 - Left wrist 28 - Left hand knuckle 29 - Left index knuckle 30 – Back 31 - Right ear 32 - High head 33 - Left ear 34 - Internal right foot 35 - Right foot big toe 36 - Internal left foot 37 - Left foot big toe		
Centres of Mass (*CMs*) **(*Vaughan-Ambrosio* BSP model)**	1 – Hip 2 – Torso 3 – Neck 4 – Head 5 - Right arm 6 - Right forearm 7 - Right hand 8 - Left arm 9 - Left forearm 10 - Left hand 11 - Right thigh 12 - Right shank 13 - Right foot 14 - Left thigh 15 - Left shank	-x displacement -y displacement -z displacement -x velocity -y velocity -z velocity -x acceleration -y acceleration -z acceleration	-x displacement -y displacement -z displacement

	16 - Left foot 17 - Right forefoot 18 - Left forefoot 19 – TOTAL BODY		
Centres of Mass (*CM*s) **(*Dumas* BSP model)**	1 – Hip 2 – Torso 3 – Head & Neck 4 - Right arm 5 - Right forearm 6 - Right hand 7 - Left arm 8 - Left forearm 9 - Left hand 10 - Right thigh 11 - Right shank 12 - Right foot 13 - Left thigh 14 - Left shank 15 - Left foot 16 - TOTAL BODY	-x displacement -y displacement -z displacement -x velocity -y velocity -z velocity -x acceleration -y acceleration -z acceleration	-x displacement -y displacement -z displacement
Centres of Pressure (*COP*s)	COP	-x displacement -y displacement	-
Distance between the Total body CM (at z = 0) and the COP (*CM – COP*)	CM - COP	-x displacement -y displacement	-
Anatomical Joint Angles	1 - Right hip 2 - Left hip 3 - Right knee 4 - Left knee 5 - Right ankle 6 - Left ankle 7 - Right forefoot 8 - Left forefoot	-Flexion/Extension angle -Abduction/Adduction angle -Internal/External rotation angle -Flexion/Extension velocity -Abduction/Adduction velocity -Internal/External rotation	-

		velocity	
Segment data	1 – Hip 2 – Torso 3 – Neck 4 – Head 5 - Right arm 6 - Right forearm 7 - Right hand 8 - Left arm 9 - Left forearm 10 - Left hand 11 - Right thigh 12 - Right leg 13 - Right foot 14 - Left thigh 15 - Left leg 16 - Left foot 17 - Right foot tip 18 - Left foot tip	-Segment X angular velocity -Segment Y angular velocity -Segment Z angular velocity -Segment X angular acceleration -Segment Y angular acceleration -Segment Z angular acceleration	-
Forces/Torques	Forces/Torques	-x Force -y Force -z Force -x Torque -y Torque -z Torque	-

Table 5-2. Parameters lists, list boxes and pop-up menus definition

5.3.3 Toolbar

We have yet described the functions related to the “New File” and “Open File”; there are other simple functions reported in the Toolbar, in the left upper part of the GUI; these functions are: “Zoom In” and “Zoom Out”, in order to apply zoom on the graph; “Pan”, that allows movements on the graph; “Rotate 3D”, making possible to rotate the graph around the axis; ―Data Cursor", that can be used like a pointer on the graph trajectories, giving back the pointed coordinates (*Figure 5-28*).

Figure 5-28. Toolbar's icons

CHAPTER 6

CONCLUSIONS AND FUTURE DEVELOPMENTS

6.1 Conclusions

In this work, we have presented a Graphical User Interface (GUI), developed in Matlab environment, aimed at assisting the Gait Analysis. The user can benefit of several advantages from the created device:

- It is no needed to develop specific codes for data analysis;
- Cameras' and force plates' data are put together and automatically synchronized;
- It is possible to check the correct markers position using a graphical approach;
- It is possible to chose among different Anthropometric measures and BSP models;
- Different filtering techniques are present, with the chance of set their features;
- A video with a model performing the captured motion is provided;
- It is possible to plot different parameters and to export data;
- It is not necessary to recur to specific software packages, it is needed just the Matlab platform.

6.2 Future developments

In order to provide a better GUI device, reducing the gap with the existing human movements platforms (reported in the *Chapter 2*), the future developers could work on the points that follow:

- First of all, like reported in the previous section, the GUI's routines should adapt to different capture systems, allowing the user to work, for example, with different number of markers, force plates, number of cameras, capture software, etc.;
- In order to provide a more powerful device, the cooperation with modelling software like OpenSim, could give good results;
- The user should have the opportunity of working also on the upper body segments' angular kinematics; now it is available just for the lower part, thanks to Vaughan *et al*. (1992) equations;
- A very important step could be the introduction of the *Kinematical consistency* for the treated models, actually available for Matlab, for UPC studies, just in 2D models while not for 3D ones;
- The GUI should allow the user to chose among more parameters, like different filtering techniques or more BSP models;
- In order to provide more realistic results, the GUI should allow the direct introduction of the Anthropometric measurements, in way to customize the gait analysis for each subject;
- Some improvement could be introduced on the interfaces' display, as well as new tools for data elaboration and visualization and adjustments on Matlab routines, in order to reduce the computational time.

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APPENDIX A

In the *Table A-1* we report the definition of the segment lengths and of the origins of the segment coordinate systems (SCSs)—values of the segment length L (used for scaling) and of the scaling factors for the segment mass m, the position of centre of mass, the moments of inertia and the products of inertia (i denotes negative product of inertia) [Dumas et al., 2007a].

Segment	Length definition	Origin of SCS	Gender	Length L (in mm)	Scaling factor for mass	Scaling factors for position of centre of mass			Scaling factors for tensor of inertia					
					m (%)	X (%)	Y (%)	Z (%)	r_{xx} (%)	r_{yy} (%)	r_{zz} (%)	r_{xy} (%)	r_{xz} (%)	r_{yz} (%)
Head & Neck	*CJC* to *HV*	*CJC*	F	221	6.7	−7.0	59.7	0	32	27	34	6(i)	1	1(i)
			M	244	6.7	−6.2	55.5	0.1	31	25	33	9(i)	2(i)	3
Torso	*CJC* to *LJC*	*CJC*	F	429	30.4	−1.6	−43.6	−0.6	29	27	29	22	5	5(i)
			M	477	33.3	−3.6	−42.0	−0.2	27	25	28	18	2	4(i)
Arm	*SJC* to *EJC*	*SJC*	F	243	2.2	−7.3	−45.4	−2.8	33	17	33	3	5(i)	14
			M	271	2.4	1.7	−45.2	−2.6	31	14	32	6	5	2
Forearm	*EJC* to *WJC*	*EJC*	F	247	1.3	2.1	−41.1	1.9	26	14	25	10	4	13(i)
			M	283	1.7	1.0	−41.7	1.4	28	11	27	3	2	8(i)
Hand	*WJC* to midpoint between MH_2 and MH_5	*WJC*	F	71	0.5	7.7	−76.8	4.8	63	43	58	29	23	28(i)
			M	80	0.6	8.2	−83.9	7.4	61	38	56	22	15	20(i)
Pelvis	*LJC* to projection of *HJC* in sagittal plane	*LJC*	F	107	14.6	−0.9	−23.2	0.2	91	100	79	34(i)	1(i)	1(i)
			M	94	14.2	2.8	−28.0	−0.6	101	106	95	25(i)	12(i)	8(i)
Thigh	*HJC* to *KJC*	*HJC*	F	379	14.6	−7.7	−37.7	0.9	31	19	32	7	2(i)	7(i)
			M	432	12.3	−4.1	−42.9	3.3	29	15	30	7	2(i)	7(i)
Leg	*KJC* to *AJC*	*KJC*	F	388	4.5	−4.9	−40.4	3.1	28	10	28	2	1	6
			M	433	4.8	−4.8	−41.0	0.7	28	10	28	4(i)	2(i)	5
Foot	*AJC* to midpoint between MH_I and MH_V	*AJC*	F	165	1.0	27.0	−21.8	3.9	17	36	35	10(i)	6	4(i)
			M	183	1.2	38.2	−15.1	2.6	17	37	36	13	8(i)	0
Alternative length and origin														
Torso	C_7 to *SUP*	*SUP*	F	125	30.4	−41.1	−117.3	−1.9	98	93	98	76	16	19(i)
			M	139	33.3	−45.6	−112.1	−0.8	93	85	96	62	7	13(i)
Hand	*WJC* to FT_3	*WJC*	F	167	0.5	3.3	−32.7	2.1	27	18	25	12	10	12(i)
			M	189	0.6	3.5	−35.7	3.2	26	16	24	9	7	8(i)
Pelvis	Midpoint between *RASIS* to *LASIS*	Middle of *RASIS* and *LASIS*	F	238	14.6	−37.1	−5.0	0.1	41	45	36	15(i)	0	0
			M	224	14.2	−33.6	−14.9	−0.3	42	44	40	10(i)	5(i)	3(i)
Foot	*CAL* to TT_{II}	*CAL*	F	233	1.0	44.3	4.4	−2.5	12	25	25	7(i)	5	3(i)
			M	265	1.2	43.6	−2.5	−0.7	11	25	25	9	6(i)	0

Table A-1. BSP parameters by Dumas *et al*. (2007a)

In theTable A-2 the correct values of the segment length L and of the scaling factors for the segment mass m, the position of centre of inertia and the products of inertia of *Head & Neck* [Dumas *et al*., 2007b].

Segment	Length definition	Origin of SCS	Gender	Length L (in mm)	Scaling factors for mass	Scaling factors for position of centre of mass			Scaling factors for tensor of inertia					
					m (%)	X (%)	Y (%)	Z (%)	r_{xx} (%)	r_{yy} (%)	r_{zz} (%)	r_{xy} (%)	r_{xz} (%)	r_{yz} (%)
Head & Neck	*CJC* to *HV*	*CJC*	F	253	6.7	1.6	57.5	0.1	29	23	30	4(i)	1	0
			M	277	6.7	2.0	53.6	0.1	28	21	30	7(i)	2(i)	3

Table A-2. BSP correct values for Head&Neck, by Dumas *et al*. (2007b)