

POLITECNICO DI TORINO

Master's Degree Programme
in Automotive Engineering

Master's degree Thesis

Motion Capture Toolkit Development for
Postural Assessment



Supervisor:

Maria Pia Cavatorta

Candidate:

Giovanni Diana

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1 Introduction

1.1 Abstract

The work described in the following master's degree thesis has been carried out during a 6 months internship in FCA Manufacturing Planning and Control offices in the division of Ergonomics and Direct Manpower Analysis. The work is part of a project started in collaboration with CIM 4.0 Competence Centres, FCA (Stellantis) WCM academy and Politecnico di Torino.

A short introduction to the context in which the work is inserted is provided in the first chapter. Industry 4.0 passes through the concept of smart factory that consists of bringing into the industrial context a new vision of the way production lines can be designed and redesign and the workflow organized in light of human factors and ergonomics. New technologies create collaboration between all the elements present in the production: operator, machines and tools. The key for optimal interaction between these elements depends on proper use of these technologies and proper design of working environment. Virtual simulations help us in reproducing such interactions in a flexible environment in order to foresee possible ways to improve them before actually installing tools and equipment in the line.

Motion capture techniques have nowadays proved to be able to guarantee with sufficient accuracy the reproduction of human motion in virtual environment enabling to simulate dynamic actions of operator as well. In the main body of the thesis, a method for the effective use of Motion Capture data is proposed to derive the postural analysis and ergonomic evaluation of working tasks with the aim of aiding the process of engineering and re-engineering of production activities that involve human operation. For the purpose of the ergonomic evaluation the EAWS screening system of biomechanical overload has been used to include all types of biomechanical risk to which an operator is exposed in the performance of a work task.

In the last part, observational criteria have been followed to validate the postural angle calculation algorithm and the static posture tracking algorithm during specifically devoted experimental testing sessions. Different ways are then investigated to integrate the method

with the already existing tools for virtual simulation to support the postural analysis, validate the results and deepening the conclusions.

Aim of the thesis is to provide a tool useful for the ergonomic specialists in the process of validation of direct labour needs in terms of time and workload of the operator. In conclusion, a comparison between the already existing methods of ergonomic evaluation is performed to check the coherence between results and understand the advantages introduced with the use of Motion Capture.

1.2 Industry 4.0 and Competence Centres

Industry 4.0 market is projected to reach \$ 156.6 billion turnover by 2024 and a compound annual growth rate of 16.9% between 2019 and 2024. Market growth is mainly attributed to the development of 3D printing technologies, industrial robotics, blockchain, internet of things, industrial metrology, augmented reality, virtual reality, artificial intelligence, 5G and the digital twin model.

The establishment of a competence centre derives from a government project to support companies to face the challenges of the fourth industrial revolution. The aim is to effectively contribute to:

- the transfer of knowledge
- the creation of networks
- the dissemination of information and collaboration between companies and research organizations

To achieve these objectives, the activities of the competence centres focus on:

- orientation and training for companies
- implementation of innovation and industrial research projects
- provision of financing for technology transfer projects.

1.2.1 Competence Industry Manufacturing 4.0

The new Italian National Competence Centre for industry 4.0 (CIM 4.0), based in Turin, is dedicated to the development of all technologies and methods for the Automotive, Aerospace, ICT and Service industries. It provides strategic and operative support instruments to manufacturing- oriented companies through:

- Development of pilot manufacturing lines in the field of additive technologies and digital area
- Digital transformation of industrial processes (from design to production, from R&D to the supply chain. From cybersecurity to the blockchain) accordingly to the Industry 4.0 vision
- Provides professional training and manufacturing expertise

- Provisioning financial support with open calls for tenders

The aim is to bridge the gap between what comes out of academic research and its actual business application, in order to push skills and good practices towards technological progress and innovation.

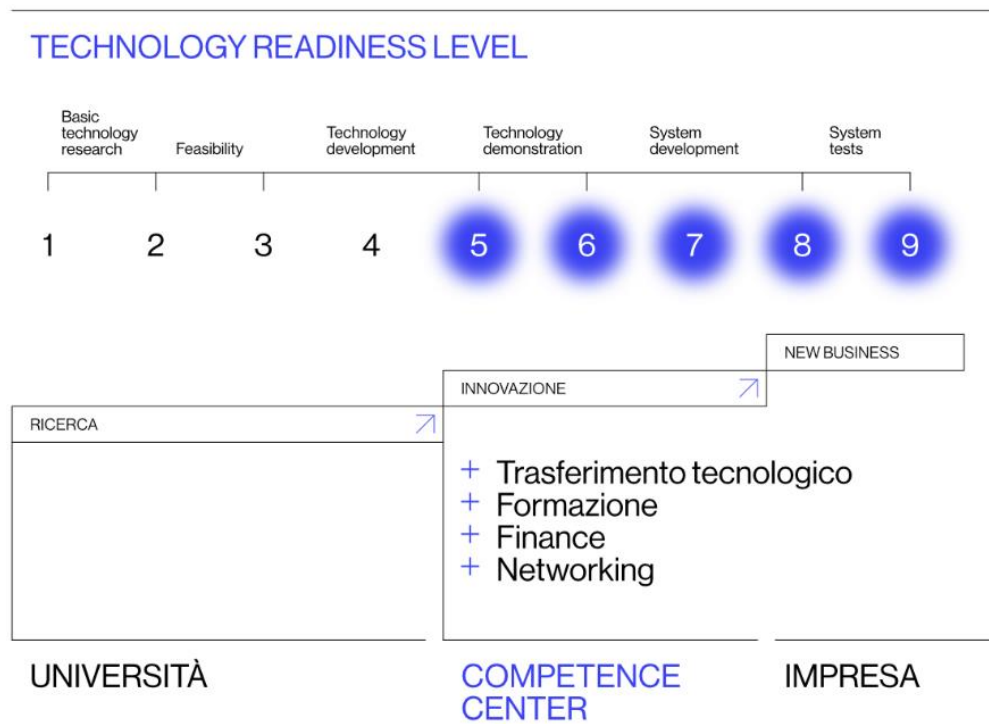


Figure 1 Competence Center placement in the field of Research & Development

1.3 Ergonomics according to FCA (Stellantis) culture



Figure 2 FCA and the new joint venture Stellantis logos

Ergonomics is that branch of science in charge of studying the “*laws of the work*” and the interactions between workers, machines and the environment in which they operate. The purpose of Ergonomics is to improve the performances of the system by designing the best possible human-machine interface and eliminating all those internal and external factors that would impede a smooth and safe production process. In FCA (now Stellantis), this is done selecting tools and equipment able to adjust to worker’s anthropometric and anatomic characteristics, but also and above all, by organizing every task so that to “*fit the worker*”’s needs and requirements.

Depending on the step of the Product Development Process (PDP), the ergonomic approach is applied in a preventive or corrective way.



Figure 3 Safety and processes side by side

1.3.1 Preventive ergonomics

Since the early stages of the design, preventive ergonomics seek for the best possible working conditions with the aim of avoiding the occurrence of criticalities before the end of the PDP. This is done by optimizing and correcting past system's solutions, or in extreme cases by completely redesign the system. The advantages of using a preventive approach are rather straightforward:

- Cost reductions
- Time savings
- Integration
- ...

Nowadays, many simulation tools are available on the market to aid and support preventive ergonomics by means of the creation of virtual environments capable of reproducing faithfully the real workplace layout where workers, schematized by manikins representing their same physical characteristics, operates in real working conditions. Thanks to these new technologies it is possible to evaluate in advance the main ergonomic risk factors.

1.3.2 Corrective ergonomics

Even the best possible design will very likely encounter some problems as it goes on through the industrialization phase. In such cases countermeasures must be applied and modifications must be introduced in order to meet the assigned targets in terms of ergonomics and consequently productivity. The biggest drawback is that, during industrialization all the design solutions are frozen and there is very limited freedom of choice in changing those solutions without affecting other components of the project, increase cost excessively and cause delays in delivering the final solution.

1.3.3 ErgoLab

To support all the aforementioned activities, in 2012 FCA (now Stellantis) founded the ErgoLab. A laboratory of Ergonomics able to reproduce on 1:1 scale real production line stations and equipment with the aim of testing and validating physical prototypes of proposed solutions, allowing to analyse them without interfering with the production activities. Physical

prototypes go now side by side with virtual prototypes. ErgoLab is equipped with the latest technology available for virtual simulations and virtual prototyping. This ensure the reproduction of virtually any type of activity carried out in the plant provided that virtual prototypes of the factory workstations are available.



Figure 4 Manufacturing ErgoLab logo

1.4 Motivation

The idea of having a tool able to be fed with motion capture data and to return an ergonomic evaluation of the task is perfectly aligned with the culture pursued by industry 4.0. The tendency to the automation of processes, the integration of new technologies to improve working conditions, productivity and quality are all key principles of the 4th industrial revolution. Moreover, the faster the validation process of work-tasks the faster is the whole Product Development Process with consequent benefits in terms of time to market. The integration with other simulations tool such as virtual reality can then save money during the testing phase of solutions. Physical prototypes would not be needed anymore since they are replaced by virtual prototypes, that are much more flexible in terms of modifications that can be applied. It is worth mentioning though, that there exist already tools devoted to this aim. Proprietary software solutions such as, MVN analyze, Visual 3D or MotionBuilder, Qualisys Track Manager or Vicon Nexus allow to visualize and analyze MoCap data. Even though none of them seemed to perfectly meet the requirements of our project objective they still proved to be very useful in validating our results.

1.5 Project requisites

Aim of the project is to develop a Unity Based Application able to handle Motion Capture data coming from sensors attached to the body of a worker as he reproduces a work cycle. The software should be able to create an animation of the skeleton of the worker properly scaled and calculate the postural angles according to the European Regulations. The software should be able to accept input data both:

1. in real time streaming, directly from the sensors through the provider's plugin
2. offline by handling previously recorded data

The Graphic User Interface should integrate the visualization of the animation and of the postural angles giving the user the possibility to navigate through the virtual environment to change the view angle perspective. The sensor that will be taken as reference for the construction of the algorithm are the MVN XSens inertial sensors. Other systems can be used as well provided that they are capable of retrieving marker's position and orientation in space in the form of, respectively, "xyz" coordinate and quaternions parameters (or Euler angles).

1.6 Project organization

The group project is formed by two ICT engineer and one Automotive engineer. The ICT team is in charge of taking care of the software GUI programming and developing. The compiler selected for the development of the software is UNITY a very flexible real time development platform that perfectly meet our requirements. The Automotive engineer instead took care of the developing of the algorithm for the calculation of the postural angles and ergonomic analysis. For the development of the “ergonomic” algorithm MATLAB computer language has been chosen with the intention of creating a toolbox made of a general set of functions suitable to handle MoCap data and that can easily be converted to UNITY computer language so that to be integrated in the final application.

2 Motion Capture overview

Motion capture (MoCap) is the process of digitally tracking and recording the movements of objects or living beings in space. The main objective of the functions that will be integrated in the toolkit is to track human motion of workers as they perform work cycles in factories and execute an ergonomic assessment. However, Motion Capture field of application range over many other disciplines:

- Sport
- Science
- Research
- Health & Medicine

There exist already proprietary software solutions available for motion capture analysis and visualization, such as Visual 3D or MotionBuilder, Qualisys Track Manager or Vicon Nexus. However, such applications are usually either too limited in their functionality, too focused on visualization and too restrictive to adapt to the specific needs of project. The need to measure joint angle in compliance with ISO and UNI EN regulations in matter of ergonomic, required the developing of a devoted “homemade” engine for postural angles calculation that could not rely on such pre-existing tools. The engine must be able to apply the biomechanical protocols required by regulation.

2.1 The sensors

To track the movements of the body and generate motion capture data to be handled in a virtual environment we need to extract information from motion sensors. There are available on the market several type of sensor each of which is most suitable for specific fields of applications. Camera based systems can be used to triangulate the location of retroreflective rigid bodies attached to the targeted subject. Depth sensitive cameras, projecting light towards an object, can estimate depth based on the time delay from light emission to backscattered light detection. Systems based on inertial sensors, electromagnetic fields and potentiometers that track the relative movements of articulated structures also exist. Hybrid systems combine different MoCap technologies in order to improve precision and reduce camera occlusions. Research has also focused on the handling and processing of high dimensional data sets with

a wide range of analysis techniques, such as machine learning, Kalman filters, hierarchical clustering and more. With such systems it is possible to build virtual prototypes of the tracked object and to estimate their segments' kinematics

2.1.1 XSens MVN

The toolkit is mainly intended to work with recordings made with Xsens MTx sensors. MTx module includes inertial and magnetic measurement units as well as 3D gyroscopes, 3D accelerometers and 3D magnetometers (38x53x21mm, 30g). The choice fell because their versatility. They can in fact be used outdoors as well as indoors, with no constrain for lightings or occlusion of markers.



Figure 5 XSens suit with seventeen sensors applied in their optimal configuration (XSens MVN Daniel Roetenberg, Henk Luinge, and Per Slycke)

2.1.2 Infrared-based Optical Systems

An alternative could be using an infrared based optical system provided that the output data are organized as described in the following sections. Such systems are based on an active source emitting pulses of infrared light at a very high frequency, which is reflected by small usually spherical markers attached to the object to be tracked (in our case workers inside their working station). With each camera capturing the position of the reflective markers in two-dimensional, a network of several cameras can be used to obtain position data in three-

dimensions. The biggest drawback of using a system like that instead of an inertial magnetic tracking system is the lack of orientation information about the tracker. Basically, optical infrared based systems are only capable of tracking 3 degrees of freedom corresponding to the translation of the objects in the space, whereas inertial magnetic systems can track up to 6 degrees of freedom including not only the translation but also the rotations.



*Figure 6 Infrared based optical sensor suits by Optitrack for Movement Sciences
(www.optitrack.com)*

2.2 Motion capture data format

MVN analyse uses a set of already available protocols for a normal communication among clients' network, specifically IP and UDP. For the communication between Xsens and Unity's plugin it is necessary that a UDP connection for the exchange of UDP packets is established on a dedicated communication channel. In order to make them readable by Unity it is necessary to know the format and the properties of each of the UDP packets. Every UDP packet contains an header of 24 byte dimension followed by a variable numbers of bytes based on the number of body segments captured. Such flexibility allows for the integration of additional equipment to extend the analysis. For example, special gloves able to reproduce a 2D map of the forces.

To build a complete package it is necessary to process the information in byte arrays and then use a hexadecimal notation to specify segment names and values related to them, in this transmission channel a big-endian notation has been used.

Header

-4 byte	PacketID
-2 byte	Message Type
-4 byte	Sample Counter
-1 byte	Datagram Counter
-1 byte	Number of items
-4 byte	Timestamp
-1 byte	Avatar ID
-1 byte	Body Segments
-1 byte	Number of Props
-1 byte	Number of fingers
-4 byte	Padding

Payload x Body Segment

-4 byte	SegmentID
-4 byte	X position
-4 byte	Y position
-4 byte	Z position
-4 byte	W orientation Quaternion
-4 byte	X orientation Quaternion
-4 byte	Y orientation Quaternion
-4 byte	Z orientation Quaternion

2.2.1 Header specification

PacketID: 4 byte to identify only the packet format, or to specify that what will be read will be a packet with a particular format with a 24-byte header and a subsequent variable payload based on the number of body segments considered. These first 4 bytes have a precise hexadecimal format that is 0x4D, 0x58, 0x54, 0x50.

Message Type: 2 bytes to specify what type of packet will be sent, then to know the payload format, for example if the payload will contain angles expressed in Euler format or angles expressed in Quaternions. Different values of message type can also be specified according to the software with which the UDP connection is interfacing, in the case of the Unity plugin it is necessary to specify 0x30 and 0x32 to indicate that the payload contains angles expressed in Quaternion, in case you want to use Euler angles you need to modify the Unity plugin scripts so that they are ready to receive the angles information in this format.

Sample Counter: 4 bytes that specify an incremental integer each time a new data packet is sent. Being a UDP connection, the receiver can lose some packets, that is, no type of check is made on the value of this field.

Datagram Counter: 1 byte useful in case the data to be sent exceeds the maximum size limited by the MTU of a UDP socket. Usually this problem does not occur, otherwise this field specifies which consecutive datagram of the same sample counter we are referring to.

Number of items: 1 byte to represent how many segments or points (if there are also props, accessories to attach to the manikin). This field is therefore a composed field made up of Body Segment + Finger Segment + Props Count.

Timestamp: 4 bytes to specify the elapsed time in milliseconds that has passed since the start of the animation, each subsequent packet will contain in this field an increased value of the milliseconds needed to process the next frame.

Avatar ID: 1 byte to identify which animation actor we are referring to, this is because the Xsens software allows you to have more actors within the animation.

Body Segments: 1 byte containing the number of character segments. Set to 23, in case fingers are not considered.

Number of Props: 1 byte containing the number of additional accessories (such as swords, weapons, etc ..) that must be attached to the mannequin.

Number of Finger Segments: 1 byte containing the number of segments of the hand in case you want to include this data in the stream as well. It assumes a value of 40 if the segments of both fingers are taken into account.

Payload specification: In the case of the payload there are differences with respect to the header, i.e. in this case the software during the construction of the package generates a payload for each body segment in the animation, for example in the case in which there are no props and the fingers are not considered segment then the overall packet will consist of 1 header and as many consecutive payloads for the number of body segments considered.

SegmentID: 4 bytes to specify which segment the position information and angles present in the payload refer to. The bytes will assume increasing values from 0 to 22 for the first 23 segments, from 24 to 27 for the props if specified, the values shown below in Table 2 for the finger segments.

Position (X,Y,Z): 4 bytes per component (X, Y, Z) that specify the coordinate values of the segment within the 3D environment.

Quaternion (W,X,Y,Z): 4 bytes per component (W, X, Y, Z) that specify the values of the angles expressed in Quaternions of the segment within the 3D environment.

Table 1: Euler and Quaternion protocols

Segment Name	Segment Index
Pelvis	0
L5	1
L3	2
T12	3
T8	4
Neck	5
Head	6
Right Shoulder	7
Right Upper Arm	8
Right Forearm	9
Right Hand	10
Left Shoulder	11
Left Upper Arm	12
Left Forearm	13
Left Hand	14
Right Upper Leg	15
Right Lower Leg	16
Right Foot	17
Right Toe	18
Left Upper Leg	19
Left Lower Leg	20
Left Foot	21
Left Toe	22
Prop1	24
Prop2	25
Prop3	26
Prop4	27

Table 2: Euler and Quaternion protocols finger tracking data additional segments

Finger Tracking Segment Name	Left Hand Index	Right Hand Index
Carpus	23 + Prop Count	43 + Prop Count
First Metacarpal	Carpus + 1	Carpus + 1
First Proximal Phalange	Carpus + 2	Carpus + 2
First Distal Phalange	Carpus + 3	Carpus + 3
Second Metacarpal	Carpus + 4	Carpus + 4
Second Proximal Phalange	Carpus + 5	Carpus + 5
Second Middle Phalange	Carpus + 6	Carpus + 6
Second Distal Phalange	Carpus + 7	Carpus + 7
Third Metacarpal	Carpus + 8	Carpus + 8
Third Proximal Phalange	Carpus + 9	Carpus + 9
Third Middle Phalange	Carpus + 10	Carpus + 10
Third Distal Phalange	Carpus + 11	Carpus + 11
Fourth Metacarpal	Carpus + 12	Carpus + 12
Fourth Proximal Phalange	Carpus + 13	Carpus + 13
Fourth Middle Phalange	Carpus + 14	Carpus + 14
Fourth Distal Phalange	Carpus + 15	Carpus + 15
Fifth Metacarpal	Carpus + 16	Carpus + 16
Fifth Proximal Phalange	Carpus + 17	Carpus + 17
Fifth Middle Phalange	Carpus + 18	Carpus + 18
Fifth Distal Phalange	Carpus + 19	Carpus + 19

Table 1 MVN XSens official documentation (MVN User Manual)

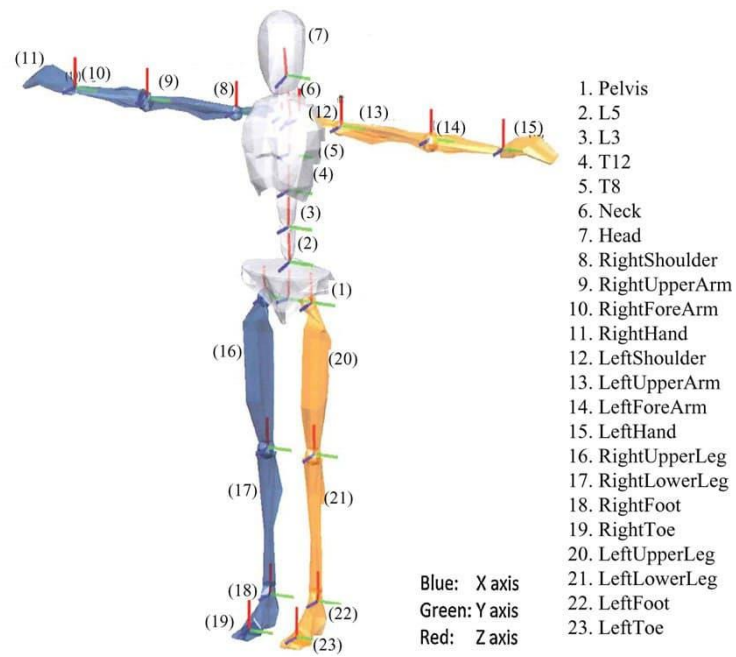


Figure 7 Segment coordinate system at each segment origin. X blue, Y green, Z red (MVN User Manual)

2.2.2 Output

For every frame of recordings, a big amount of data is collected or streamed by means of MVN plugins to UNITY that already display and simulate the virtual environment where data can be visualized. We can subdivide roughly all data into two clusters:

1. Data useful in building and visualizing motions and animations in virtual environment
2. Data useful for the purpose of the ergonomic evaluation

The output file can be exported in .XLSX or .XML format and organized in a structured way similar to that showed in Table 2.

	Sensor 1 (Segment A)						
FPS	Position (x, y, z)	Orientation (q0, q1, q2, q3)	Velocity (x, y, z)	Acceleration (x, y, z)	Joint angle	Ergo Joint angle	Center of Mass
Frame 1
Frame 2
Frame 3
...

Table 2 MVN analyze output information structure

- 1) The position is taken as XYZ coordinates of the manikin with respect to a global reference system for all the vectors
- 2) The orientation of all the sensor segments is represented by quaternions (q0, q1, q2, q3) or by Euler angles along XYZ axis of the global reference system
- 3) Velocity of the marker in every direction is taken as the derivatives of the segment position
- 4) Acceleration in every direction is taken as second order derivatives of the segment position
- 5) Joint Angles of the vectors (not the segments)
 - a) The rotation is calculated according to the order ZXY except for the shoulders XZY
- 6) Center of mass coordinates

2.3 MoCap Data acquisition

In data acquisition it is essential to carefully follow the instructions provided by the parent company to calibrate the sensors and, if possible, unequivocally establish the position and orientation of the upper limbs and the head so as to make the results of the experiments comparable. To achieve satisfactory results in terms of repeatability of the acquisitions, the software provides default procedure of the posture to be assumed during calibration:

- 1) Standing up right in N-pose neutral position (figure 6)
 - a) Upper limbs parallel to body
 - b) Straight shoulders
 - c) Neck aligned with the backbone



Figure 8 Lateral and Frontal view of neutral N-pose reference position for calibration

- 2) Standing upright in T-pose position (figure 7)
 - a) Upper limbs perpendicular to sagittal plane
 - b) Palms pointing downward
 - c) Straight shoulders
 - d) Neck aligned with the backbone



Figure 9 Lateral and frontal view of a T-pose reference position for calibration

2.3.1 Recordings

Each of the seventeen sensors calculates the position and orientations of individual body segments and thanks to the knowledge of the length of the segments based on the anthropometric data manually inserted, rotations among them can be estimated and their position can be derived under the strict assumption of a linked kinematic chain. Therefore, this method assumes an articulated rigid body in which the joints have only rotational degrees of freedom. However, a human body and its joints cannot be modelled as a pure kinematic chain with well-defined joints such as hinge-joints and ball-and-socket-joints. Thanks to the elasticity of human articulation system conferred by the ligaments and cartilage, each human joint allows some laxity in all directions (both position and orientation) other than its main direction of movement. This effect is compensated very well by describing signals and biomechanical model in a stochastic manner instead of in a deterministic one.

2.3.2 Verification of the suitability of data with respect to project requirements

Usually these sensors are intended to be used for videogaming development or special effects for the film industry. In both cases, there is no need for accurate approximation of the biomechanics of the body. In our case instead it is strictly needed to have an anthropometrical correlation between the humanoid reproduced by the sensors and the actor wearing them. The humanoid built by sensors is based on anthropometric data defined manually by the user during calibration. Unfortunately, the scaling logic of the segments followed by the plugin of the parent company is unknown and can only be obtained with a reverse process engineering with some approximation. Therefore, the correctness of the matching between the manikin scaled by the plugin and the human wearing the sensors cannot be directly certified in terms of proportions and dimensions of human segments. It would be ideal to know the scaling technique used by the software and possibly to modify it in order to align it with the anthropometric data of our user population. Unfortunately, we cannot have direct access to the source code of the plugin without the parent company permission. It is well known how important is during ergonomic risk assessment to address the analysis to the reference population involved in the investigation. To this aim we developed our own manikin whose skeleton resemble the one generated by the sensor with the difference that segments lengths and proportions can be scaled at our desire. The new manikin's markers are attached to the native manikin to maintain coherence of motion. The price to pay for that is that we cannot keep the same segment position in the space for all the markers. Only one reference marker position will be exactly the same for both manikins, the rest of them will be scaled according our instructions. They will be somewhat rigidly linked to the native manikin and they will follow their same trajectory as the record streams.

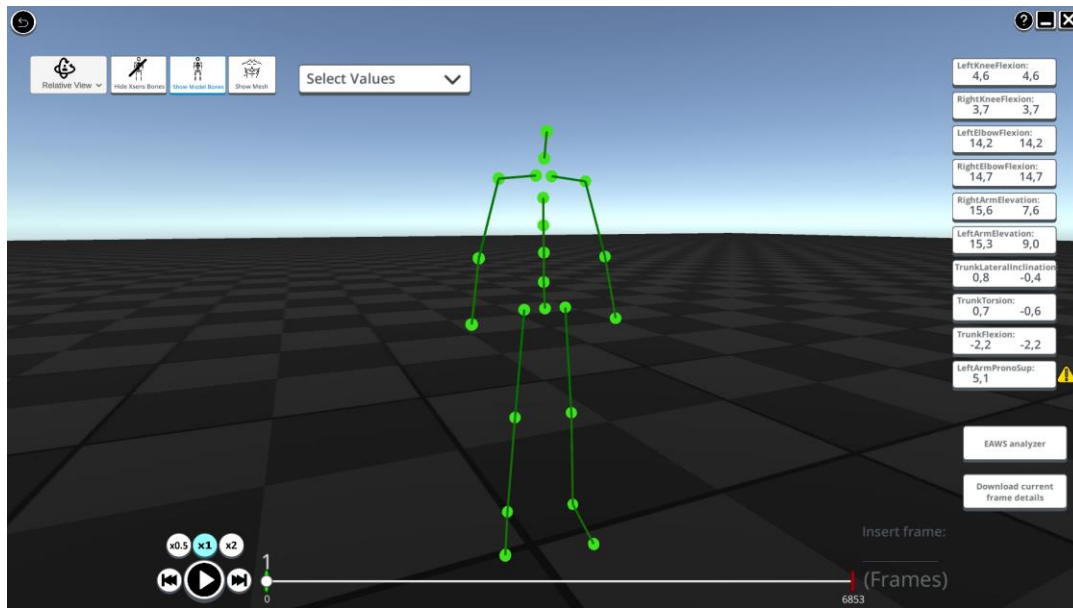


Figure 10 Xsens native manikin directly built from MoCap data coming from sensors

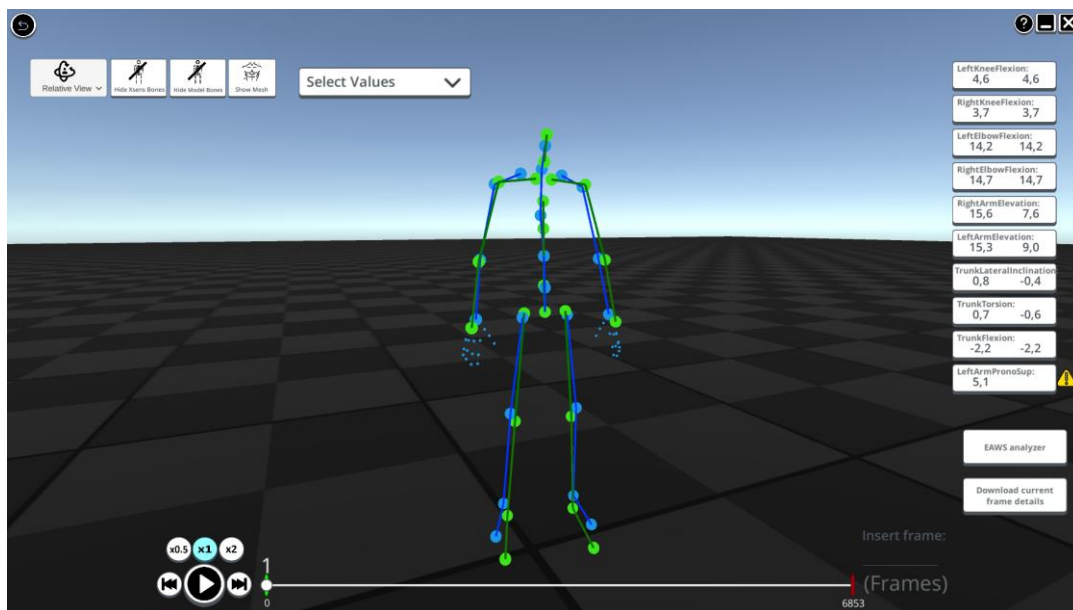


Figure 11 Mesh (blue skeleton) attached to the native manikin (green skeleton) scaled upon needs

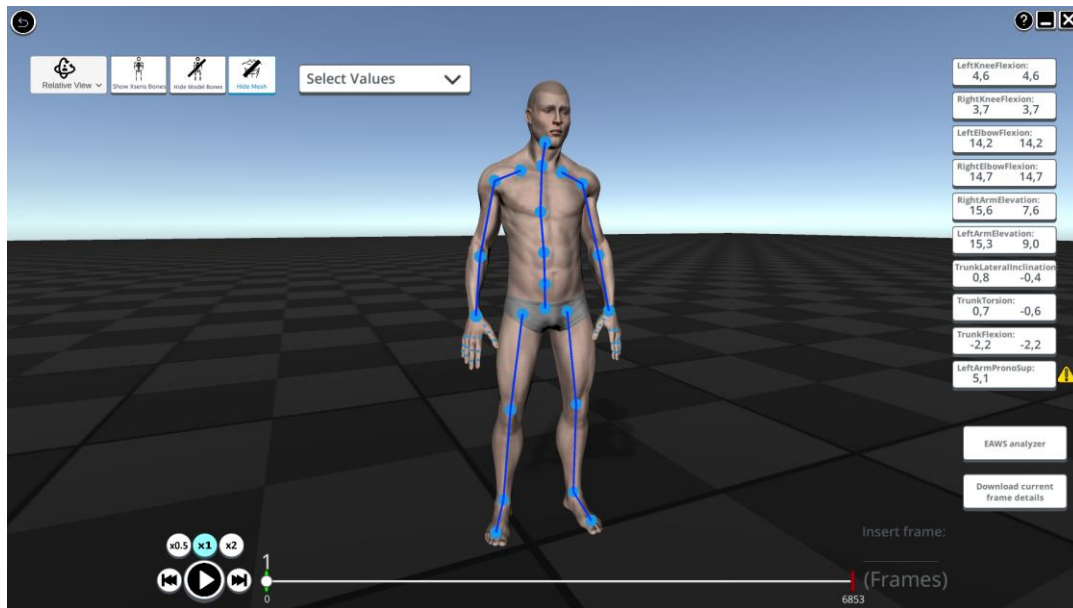


Figure 12 Skin of a humanoid attached to the mesh

2.4 Offline data recordings vs live data streaming

The final application is intended to be used mainly offline with data recordings in the format shown in previous sections and videos collected at a different time with respect to when the ergonomic analysis must be performed. However, the possibility to stream live motion capture data figure ... has been implemented in the user interface as an added value. With live data streaming it is possible for example to:

- Check calibration effectiveness
- Perform joint angles validation

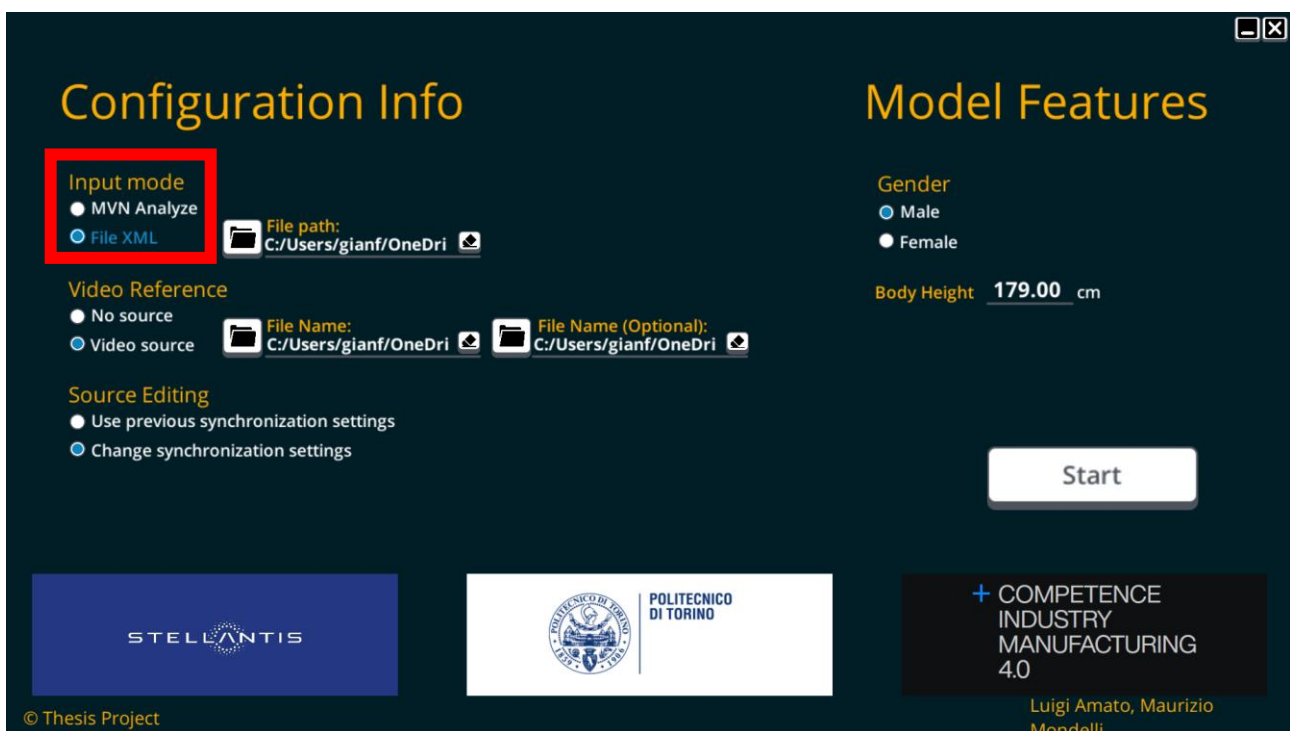


Figure 13 Input mode flag in the DEMO starting menu of the application

MVN Analyze input mode stands for the live streaming of data from the sensors to the application through a suitable plugin. In order to be functional, the network streaming setting must be enabled in the options preferences of MVN analyze. From that same setting menu, it is possible to check the UDP port identifier to which the application must be connected. Usually, this last, is set to 9763 by default but can change from machine to machine. MVN analyze input mode can be selected even though the application and the analyzer are not running on the same machine but are connected to the same network. However, it is highly recommended to have both executable running on the same machine, since each intermediary

connection add a protocol check that cause some delay to the transmission of data, not to mention connection stability issues that may arise.

The most common inconsistencies that we faced during the tests are related to drifting errors of the sensors, probably due to electromagnetic disturbances, and erroneous calibration. More rarely the error can be caused by wrong configuration of the solver at the moment of exporting the MoCap dataset.

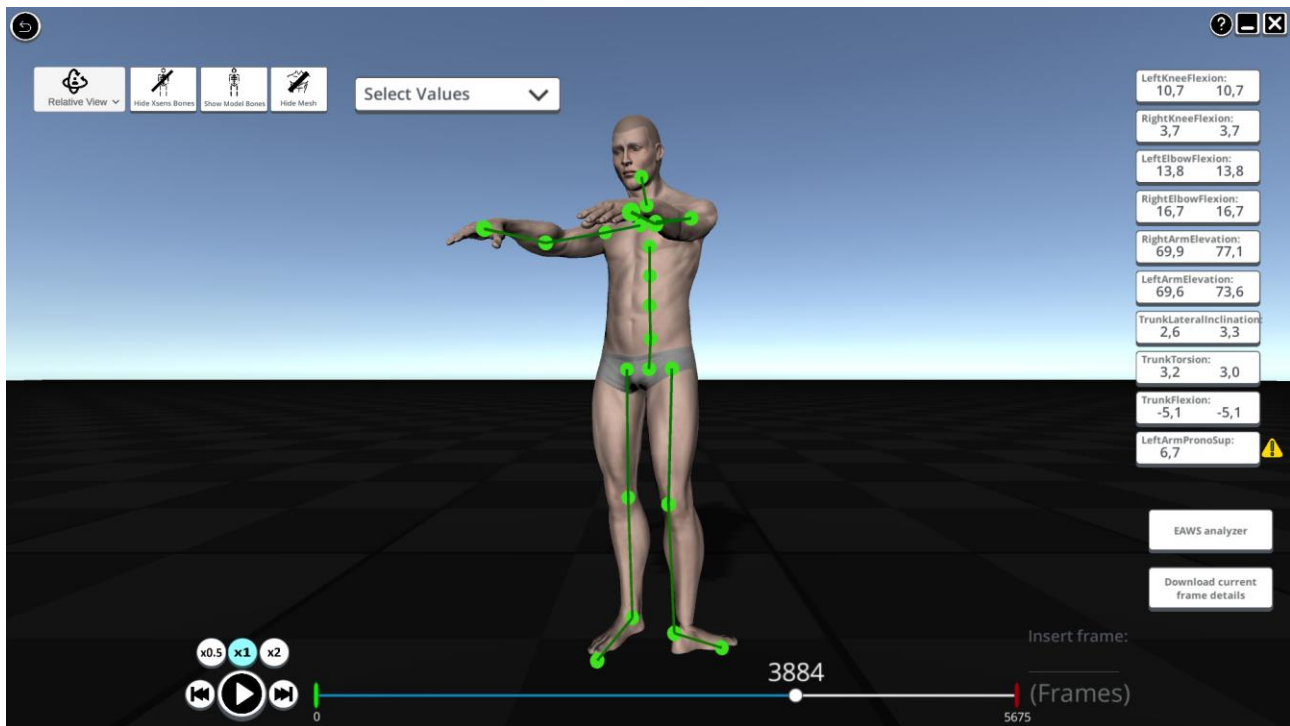


Figure 14 Example of erroneous calibration: drifting error left foot

3 Motion Capture Toolkit

3.1 Overview

For the purpose of the postural assessment a MATLAB demo has to be developed with the aim of grouping a toolkit of functions suitable to read, visualize, analyse motion capture data coming from sensors and deliver a postural analysis. MATLAB has been selected for two main reasons:

- 1) The opportunity to access numerous libraries and to use a wide range of prebuilt function to manage position and orientation data of segments
- 2) The easiness in the translation of algorithms, functions and formulas from MATLAB visual basic computer language to Unity programming language (C#)

This second reason is a necessary condition for the purpose of the final project and has been discussed with the team prior the starting of the development to study the feasibility of the integration of the functions in both the applications. The biggest drawback featured by MATLAB compared to Unity is that it does not integrate an intuitive Graphic User Interface. To interact with the functions it is necessary to run the “demo” script and to digit the index of the function that we want to implement. For example, to load a MoCap data structure into MATLAB workspace digit “1”.

MOTION CAPTURE TOOLKIT FOR POSTURAL ASSESSMENT

```
{'1) Reading, MoCap data
{'2) Visualizing MoCap data markers position (insert number
of frame to be visualized)
{'3) Visualizing MoCap data markers position and
orientation (insert number of frame to be visualized)
{'4) Generate animation video
{'5) Calculate and plot joint angles for the whole test
{'6) Calculate and visualize joint angle in desired frame
{'7) Kinematic analysis
{'8) EAWS
>> Enter number:
```

Figure 15 MATLAB command window at the start of the DEMO application

3.2 Reading MoCap Data – DEMO 1

```
{ '1) Reading, MoCap data
```

Once that data have been recorded in the xml or xlsx output export file format described in the previous section the first thing to do is to arrange them in such a way to make it easier to build our manikin and to save it into variables easy to be handles by MATLAB compiler. To this aim the markers segments are rearranged so that to respect the order with which they will be connected to resemble the human skeleton. For example, the marker's coordinates that compose the spine from the sacrum to the atlas will be displayed and numbered in a sequenced manner. The same is done from the right hand to the left hand passing through the neck and from the right toe to the left toe passing through the pelvis. Segment position and orientation data are saved into matrices of dimension “25 x number of frames”. Every row of such matrix represents the position and orientation of the markers in one frame. Other information such as the number of frames of the recording and the number of segments of the MoCap data structure are saved in specific variables and will be frequently called in the following functions.

3.3 Visualizing MoCap Data Marker's position – DEMO 2

```
{ '2) Visualizing MoCap data markers position (insert number  
of frame to be visualized)
```

The coordinates of the segments can be quickly read by the compiler in a sequenced manner and using simple pre-built MATLAB functions it is possible to plot the markers connected by segments. The result should resemble a schematized human skeleton composed of 22 segments connecting the 23 markers. (figure 16). This is useful to check whether the data structure have been read properly.

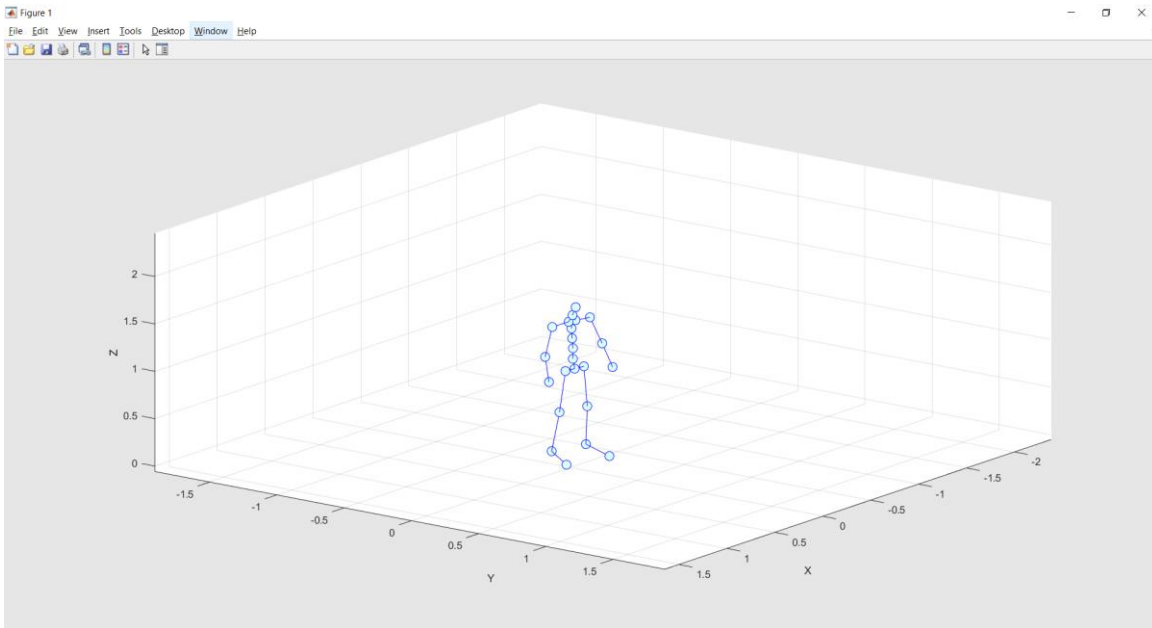


Figure 16 DEMO 2 output figure

This procedure can be repeated for every frame of recording by inserting the desired frame in the input line of the prompt command window.

3.4 Visualizing MoCap data Marker Orientation – DEMO 3

```
{'3) Visualizing MoCap data markers position and orientation
(insert number of frame to be visualized)
```

The previous representation only allows to visualize the changes in position of the markers whereas the orientation cannot be appreciated. The information about segment orientation can be retrieved either by the quaternions or directly by the Euler angles calculated by the sensors and stored in the recordings. We opt for the quaternions for the simple reason that MATLAB offers pre-built functions to handle quaternions and to get transformation matrices with which we can move vectors in the space according to their orientation. Each marker rotation is identified by 4 parameters q_0 q_1 q_2 q_3 , with which it is possible to build a rotation transformation matrix from a fixed reference system to the state of the marker. Thanks to such information we can build local reference system per each marker (figure 17) so that to see not only how they are positioned but also how they are oriented in space.


```
global_ref_sys=[0.1 0 0;0 0.1 0;0 0 0.1];
```

```
local_ref_sys=quatrotate(quat_n(k(i):k(i)+3),global_ref_sys)+  
marker_position;
```

where `quat_n` stands for the row of quaternions containing the orientation information about frame n and $k(i)$ is the marker identifier of parameters q_0 q_1 q_2 q_3 . (See appendix for more theory about quaternions)

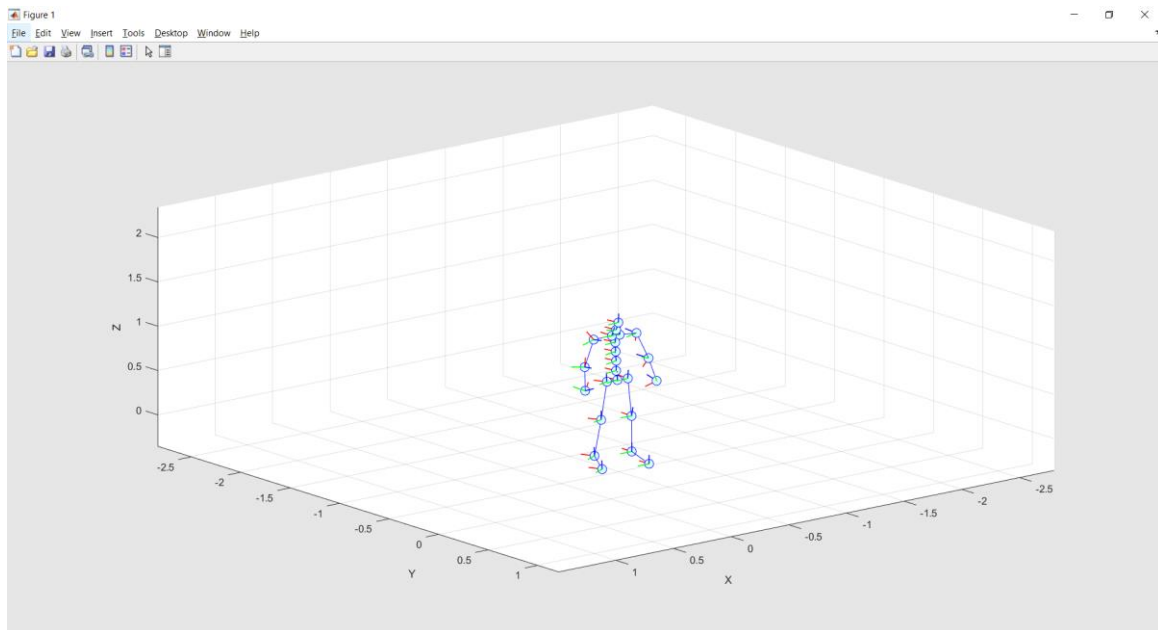


Figure 17 DEMO 3 output figure

3.5 Animation generation – DEMO 4

```
{'4) Generate animation video
```

With both representations it is possible to create an animation movie by simply writing in an iterative way frame by frame the recordings data in a video file that is then saved in “.avi” format. It is set by default the configuration with marker’s local reference system so that to appreciate also the rotations of body segments. The video helps us to verify the coherence between the movements performed during the test when data has been recorded, and the movements of the model built on MATLAB as it reads the streaming of data recorded.

3.6 Joint angles evaluation – DEMO 5

```
{'5) Calculate and plot joint angles for the whole test
```

For the evaluation of postures, it is fundamental to build a robust algorithm capable of extracting joint angle in every configuration of the manikin in the space. To achieve that the following functions have been set up.

```
function alpha=threeD_angle(P1,P2,P3)
P32=P3-P2;
P12=P1-P2;
d=dot(P32,P12);
alpha=rad2deg(acos(d/(sqrt(sum(P32.^2))*sqrt(sum(P12.^2)))));
```

```
function alpha=threeD_angle_segm(P12,P32)
d=dot(P32,P12);
alpha=rad2deg(acos(d/(sqrt(sum(P32.^2))*sqrt(sum(P12.^2)))));
```

These functions return an angle in degrees given as input two segments in space in vectorial form or three point in space in vectorial form. The three points or the two segments are identified by XYZ coordinates. P1 could be assumed as the data frame of numeric values containing the X, Y, and Z coordinate data of the first point, for example the shoulder, P2 the data frame of numeric values containing the X, Y, and Z coordinate data of the second point which is assumed to be the vertex of the angle, for example the elbow, and last P3 the data frame of numeric values containing the X, Y, and Z coordinate data of the third point, in our example the wrist. Hence, the fundamental assumptions beyond these functions are that

1. XYZ vectors for each marker of the manikin is known and stored for every frame.
2. P1 is the most proximal joint, P2 is the middle joint and P3 the most distal joint

The formula that allows to get the final angle is simply the application of a fundamental relation of analytical geometry in space that express the scalar product and the vectoral product among two vectors as the product between the Euclidean norm of the vectors and the cosine (scalar) or the sine (vectoral) of the angle they form. The choice of the arccosine

trigonometric function rather than the arcsine or the arctangent fell because of its codomain included in $[0; \pi]$ which is almost always the case when dealing with anatomical joint angles.

$$||\vec{v} \cdot \vec{w}|| = ||\vec{v}|| \cdot ||\vec{w}|| \cdot \cos\vartheta$$

$$\vartheta = \arccos\left(\frac{||\vec{v} \cdot \vec{w}||}{||\vec{v}|| \cdot ||\vec{w}||}\right)$$

The power of this formula is that from now on we can calculate any of the joint angle requested for the ergonomic evaluation provided that we know at any time the proximal, the middle and the distal joint coordinates. The most challenging part is to select such three points or directly the two segments forming the angle in such a way to calculate the desired angle in accordance with the regulation even in case of strange mixed postures assumed by the manikin. This can be achieved only if solid reference planes and axis that move together with the manikin are built.

3.6.1 Anatomical reference planes and axis

For the identification and selection of the points and the segments with which to calculate joint angle several reference plane and axis have been built to aid in the construction of the angles in compliance with the directives of the norms UNI EN 1005-4 and ISO 11226.

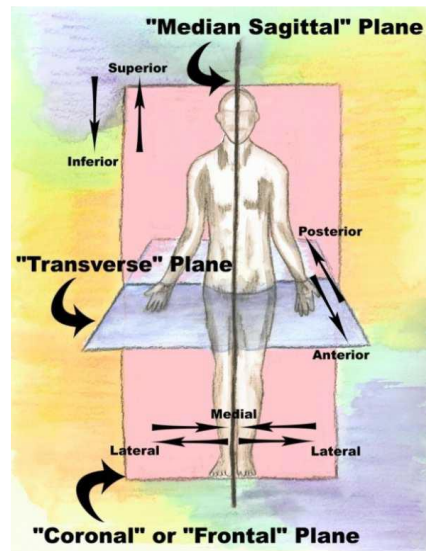


Figure 18 Anatomical Planes and Axis

1. “Median Sagittal plane”: Vertical plane perpendicular to segment connecting the hips and passing through pelvis
2. “Coronal or Frontal plane”: Vertical plane parallel to segment connecting hips and passing through pelvis
3. “Transverse plane”: plane perpendicular to trunk (segment connecting pelvis and neck) passing through pelvis

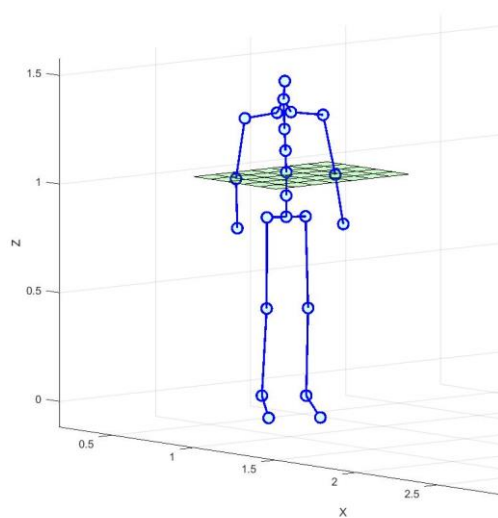
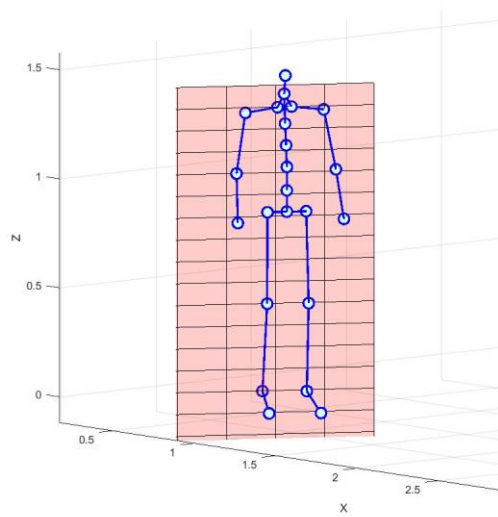
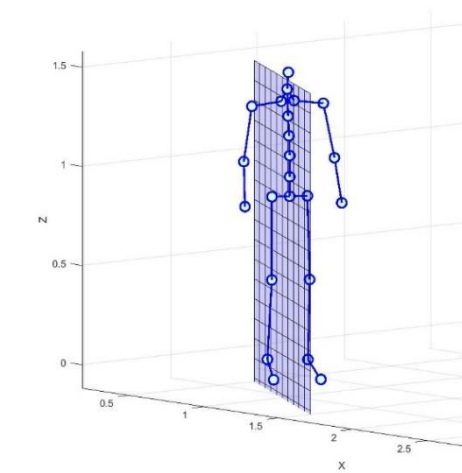


Figure 19 Anatomical reference Planes and Axis in MATLAB

3.6.2 Trunk flexion-extension

The trunk flexion extension has been calculated as a vertical inclination of the segment connecting the pelvis and the neck projected to the median sagittal plane of the manikin. To make distinction among flexion (positive angle) and extension (negative angle), we used as discriminating element the vector pointing from the vertical projection of the pelvis at the height of the neck towards the actual position of the neck. By comparing this vector with another vector starting from pelvis and pointing in perpendicular direction to the anterior side of the frontal plane we know whether we find ourselves in a flexion rather than an extension case. The segments can be visualized in figure 20.

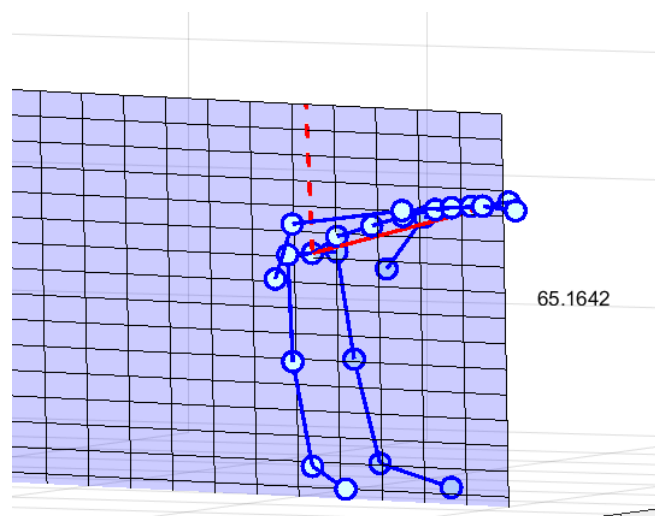
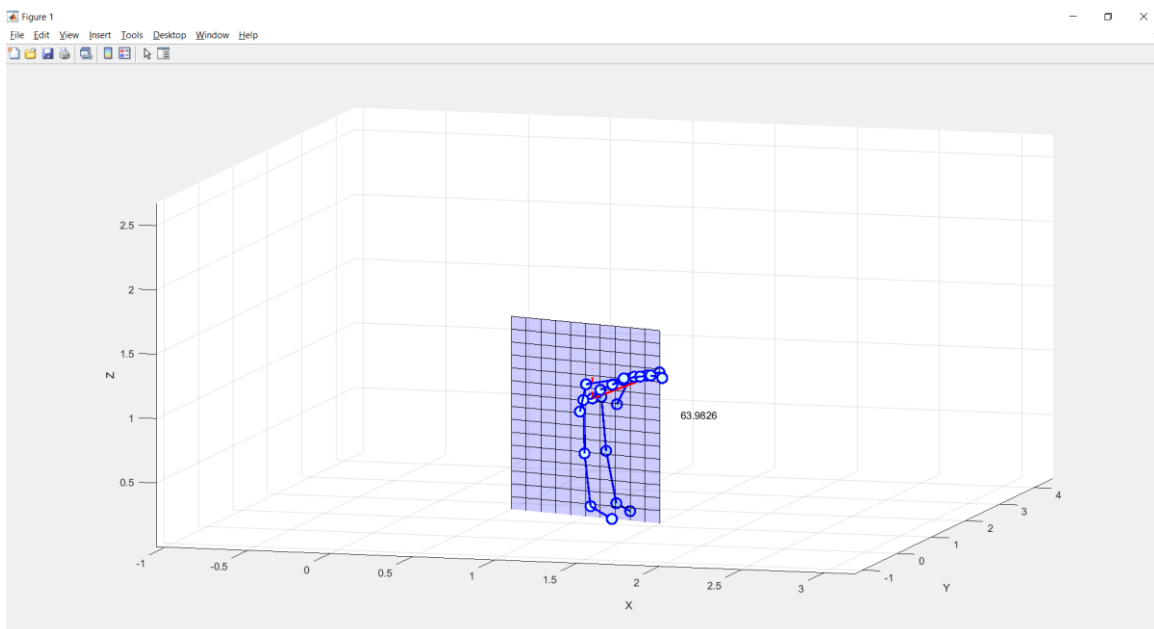


Figure 20 Trunk flexion segments

3.6.3 Trunk lateral inclination

The trunk lateral inclination has been calculated as the vertical inclination of the segment connecting the pelvis with the neck projected to the frontal coronal plane of the manikin. Figure 21.

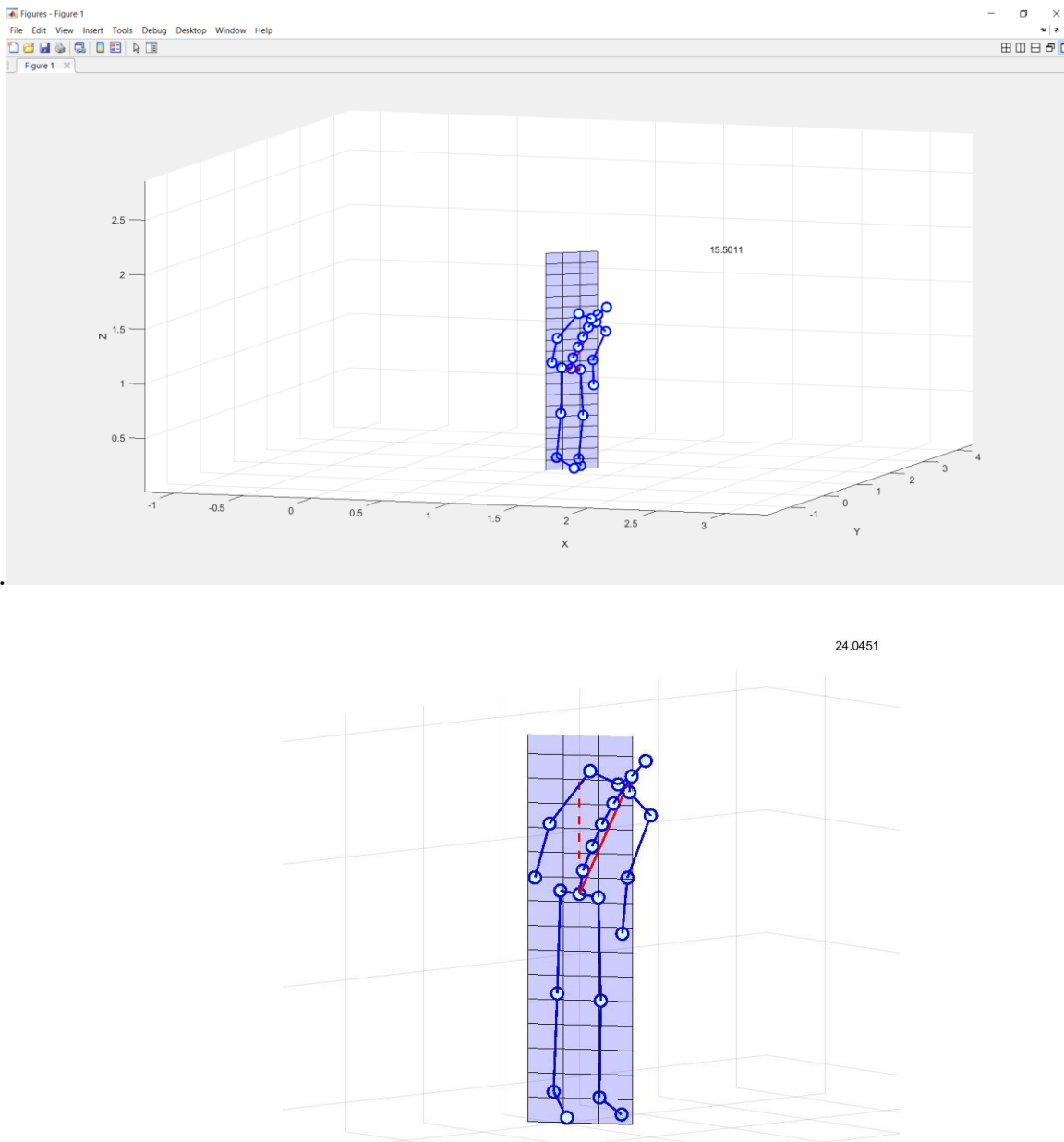


Figure 21 Trunk lateral inclination segments

3.6.4 Trunk torsion

Trunk torsion has been intended as the rotation of the shoulders with respect to the hips about the trunk. Therefore, the angle formed by the segment connecting the hips and segment

connecting the shoulders projected on a plane perpendicular to the trunk. In this way only the rotation about Z local axis of the manikin is considered. The projected segments can be visualized in figure 22, the red one as the one of the hips and blue one as the one of the shoulders

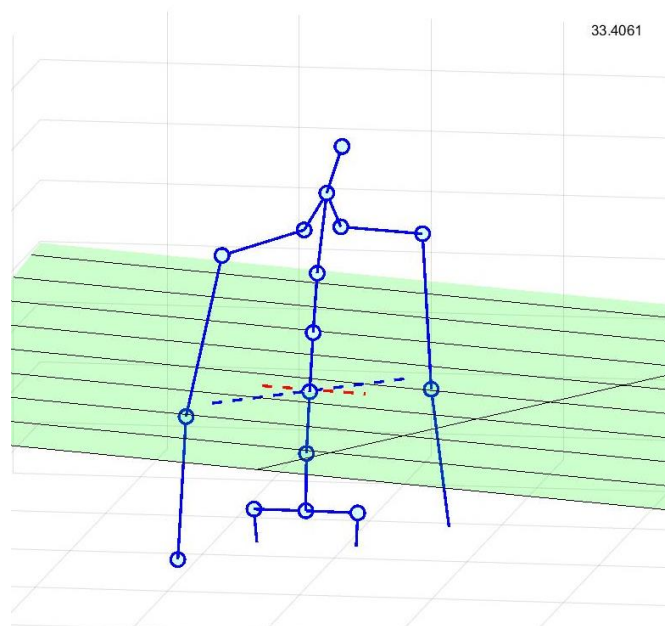
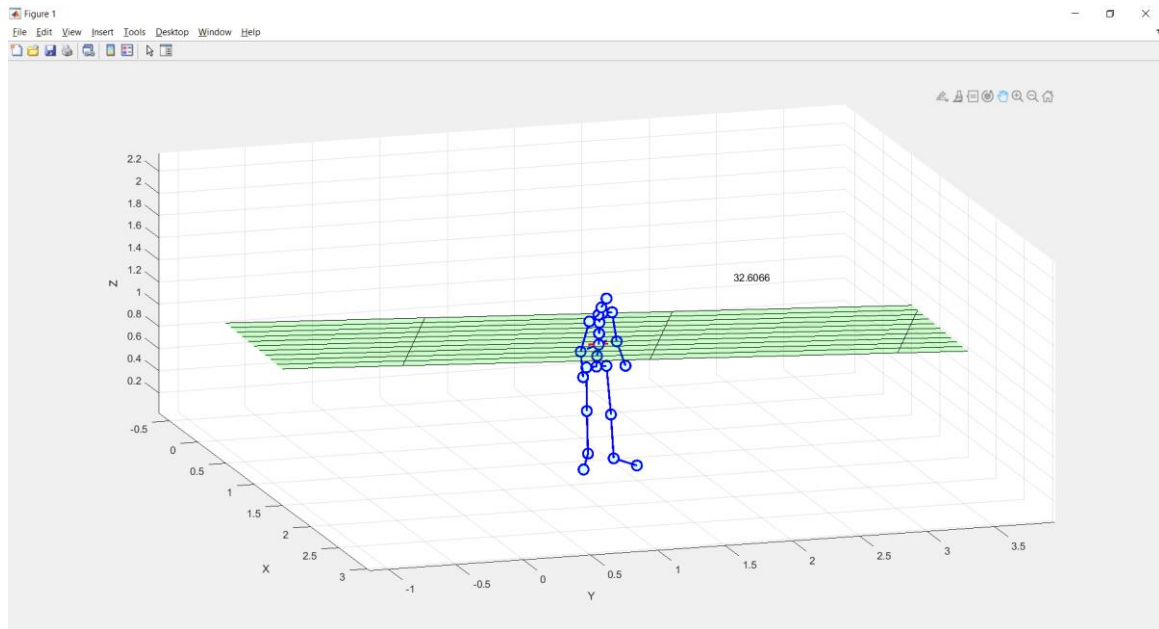


Figure 22 Trunk torsion segments

3.6.5 Upper limbs elevation

Different definitions of work with arm elevation are found in literature. In this report arm elevation stands for the angle between the upper arm vector (humerus bone) and the segment connecting the pelvis with the neck. The angle formed in this way can be visualized in figure 23.

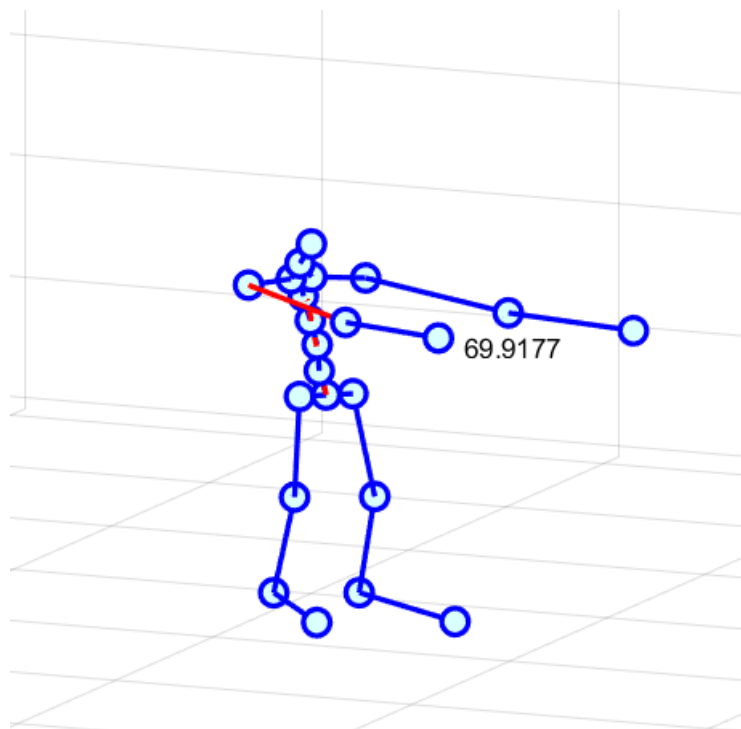
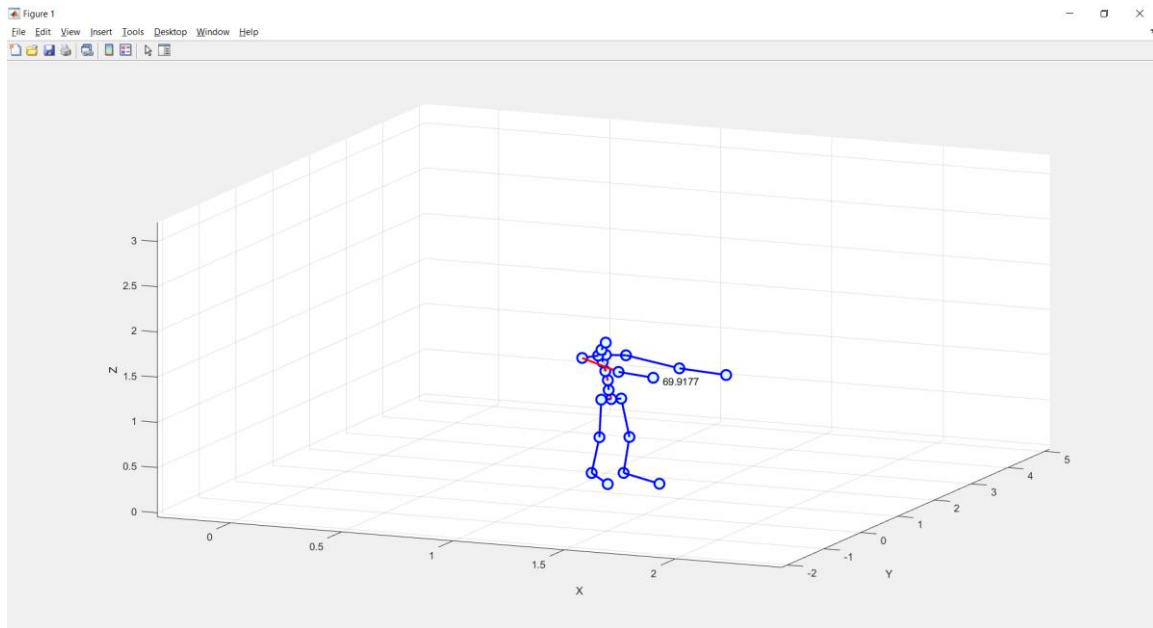


Figure 23 Arm elevation segments

The same holds symmetrically for left and right arm. Notice that, to make sure the calculation is insensitive to any trunk bending the segment connecting neck and pelvis has been chosen instead of a simple vertical axis as the “zero-position” for reference posture. Moreover, even though the 3D arm angle comprises both abduction and frontal elevation of the arm and none of the two regulations taken into account in this report require to make distinction between the two, it is worth calculating them separately to have a more precise idea of the posture assumed by manikin.

3.6.6 Arm abduction

Arm abduction has been calculated as the angle included among the upper arm segment projected on the frontal plane and the neck-pelvis segment projected on the same plane. The outcome can be visualized in the figure 24 below in a posture where arm abduction is particularly relevant.

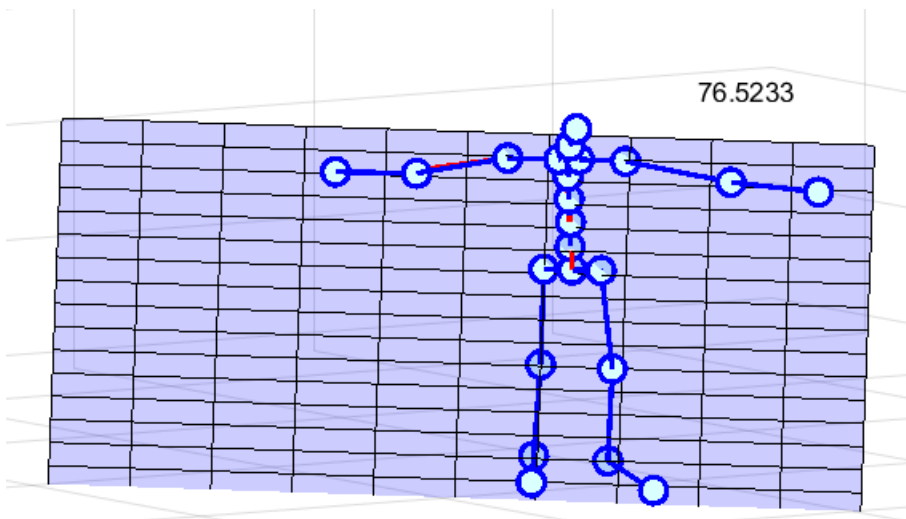
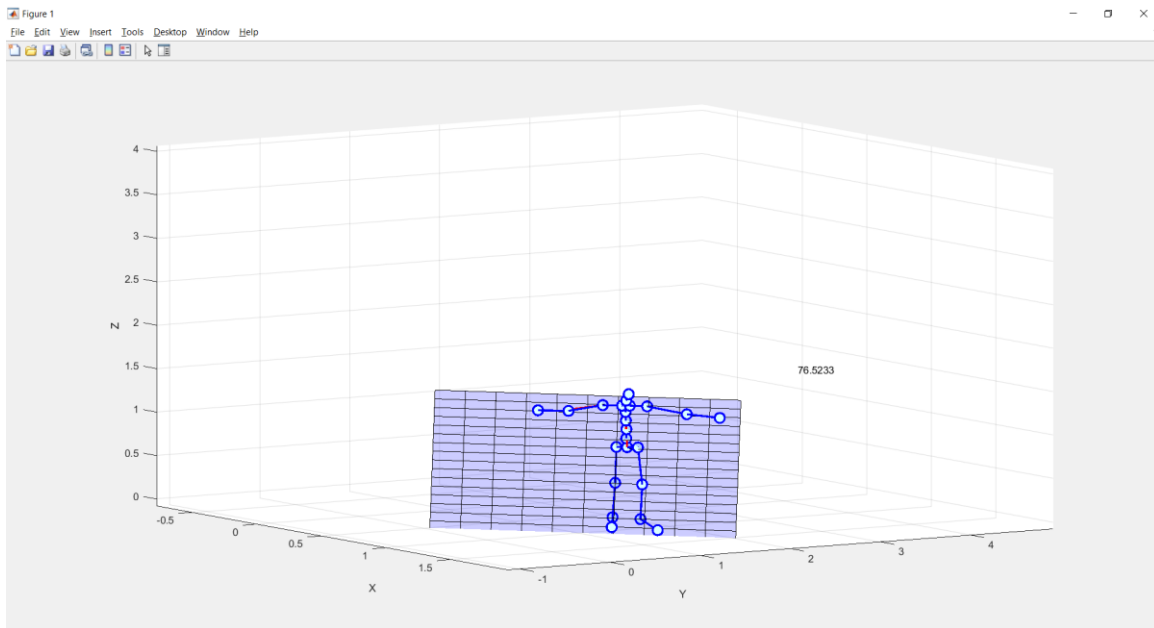


Figure 24 Arm abduction segments

3.6.7 Arm flexion

Arm flexion is the angle formed in the lateral plane by the projections of the segment connecting the pelvis and the neck and the segment connecting the shoulder to the elbow. The

angle obtained in such a way can be visualized in the figure 25 below in a posture where arm flexion is particularly relevant.

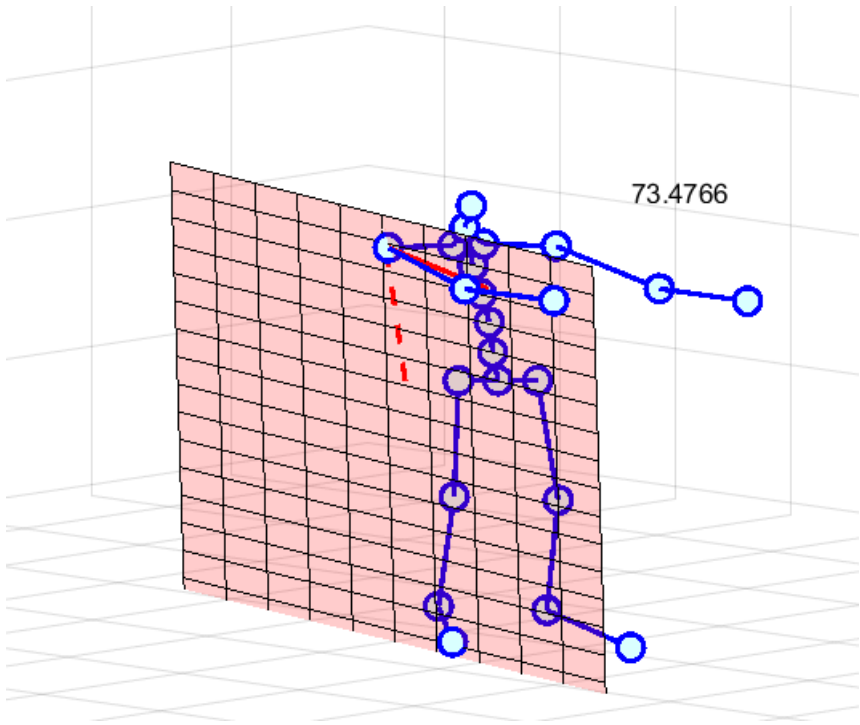
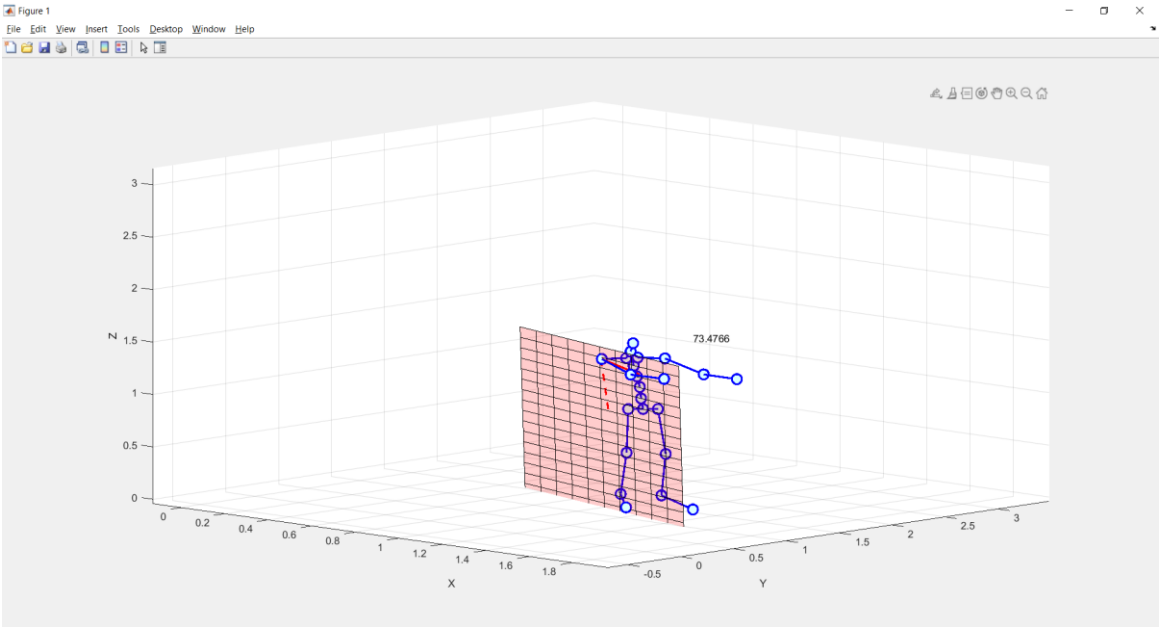


Figure 25 Arm flexion segments

3.6.8 Elbow flexion

The elbow flexion is simply obtained by subtracting the angle formed by the three markers of the arm, shoulder elbow and hand to 180° that represent the posture of the arm when is completely extended. Considering that the elbow joint is a simple hinge there is no need for projecting the points in none of the reference plane and the function can be directly fed by the coordinates of the markers.

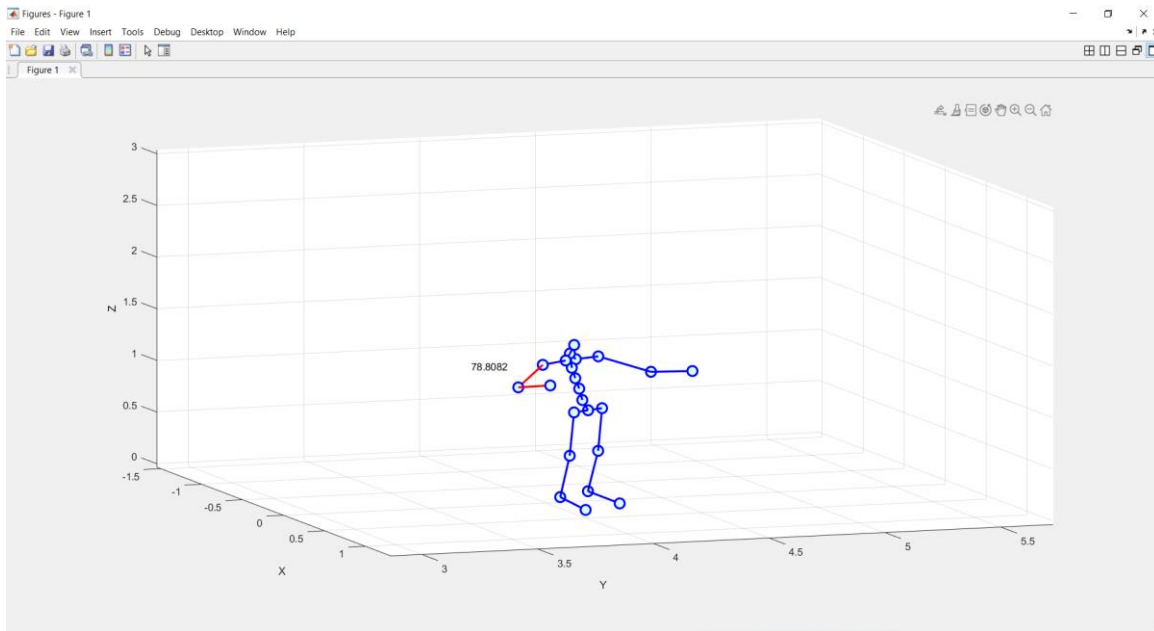


Figure 26 Elbow Flexion segments

3.6.9 Knee flexion

The knee flexion is simply obtained by subtracting the angle formed by the three markers of the leg, hip knee and foot to 180° that represent the posture of the leg when is completely extended. Considering the knee joint as a simple hinge there is no need for projecting the points in none of the reference plane and the function can be directly fed by the coordinates of the markers.

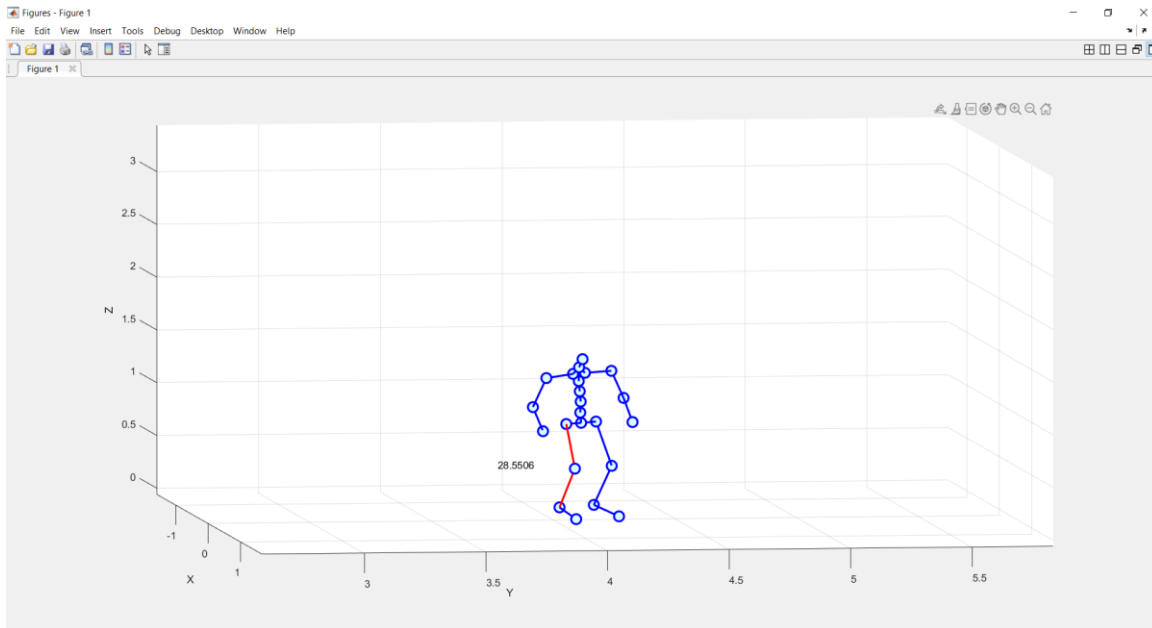
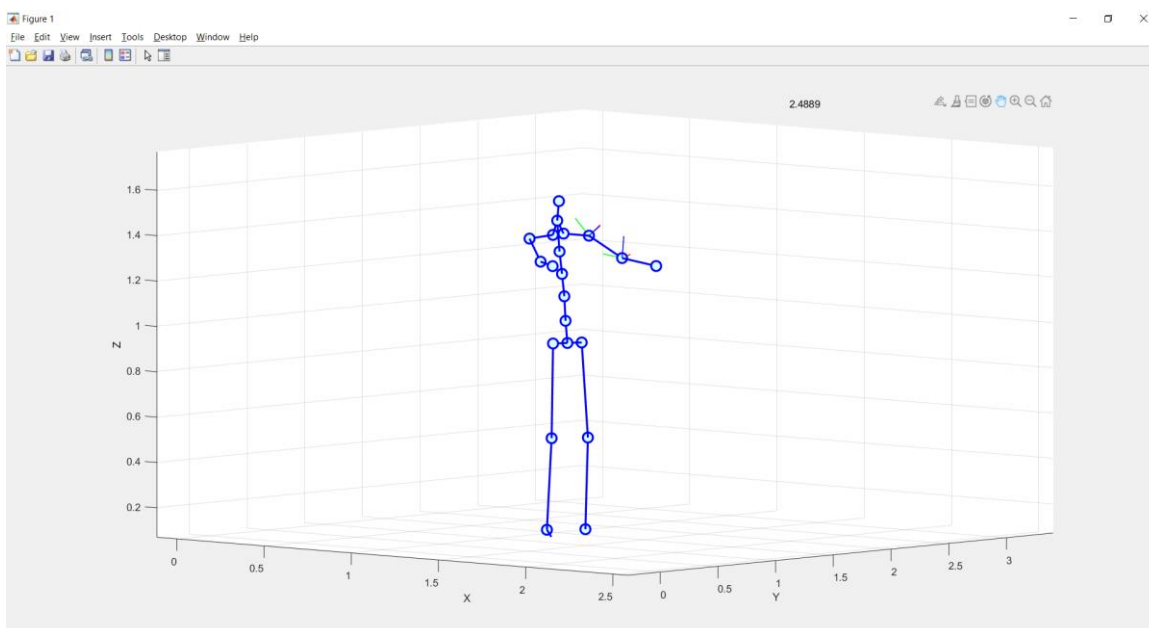


Figure 27 Knee Flexion segments

3.6.10 Arm Prono-supination

Pronation supination is the rotation of the wrist around the axis of the forearm. It is important to bear in mind that it is not just the wrist that rotates but the whole forearm including both ulna and radius bones. This is critical in the choice of the marker orientation representative of the angle. We will not compare the orientation of hand marker and elbow marker for the purpose but the orientation of the shoulder marker and elbow marker figure 28.



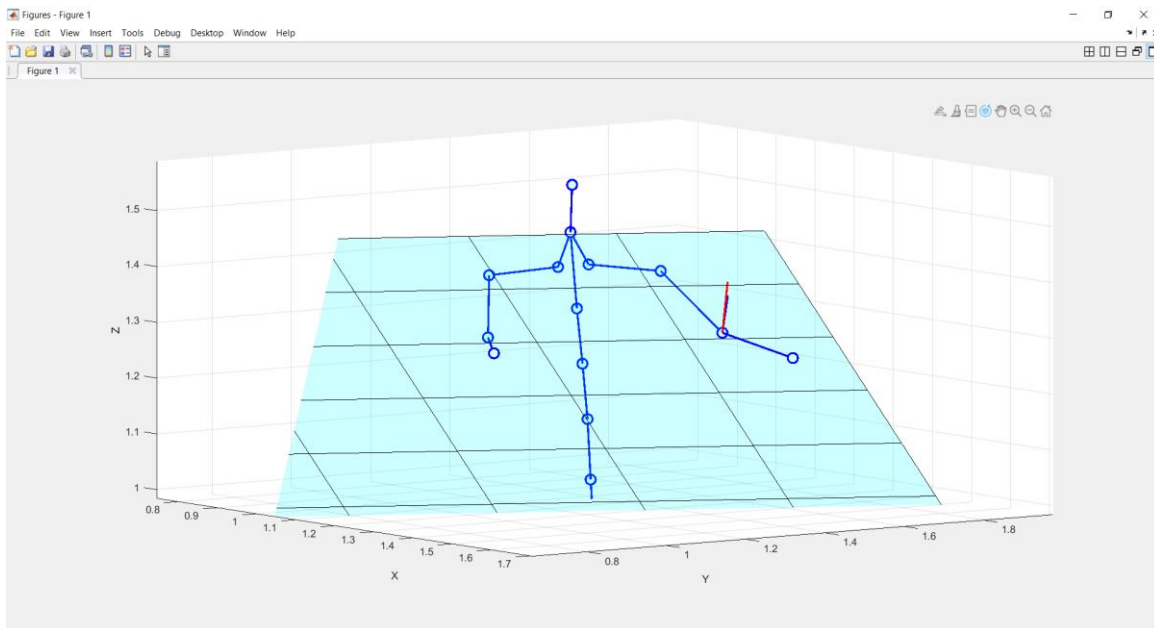


Figure 28 Arm pronation-supination segments

The segments that form the angle are the z projections of local reference system of elbow and shoulder markers.

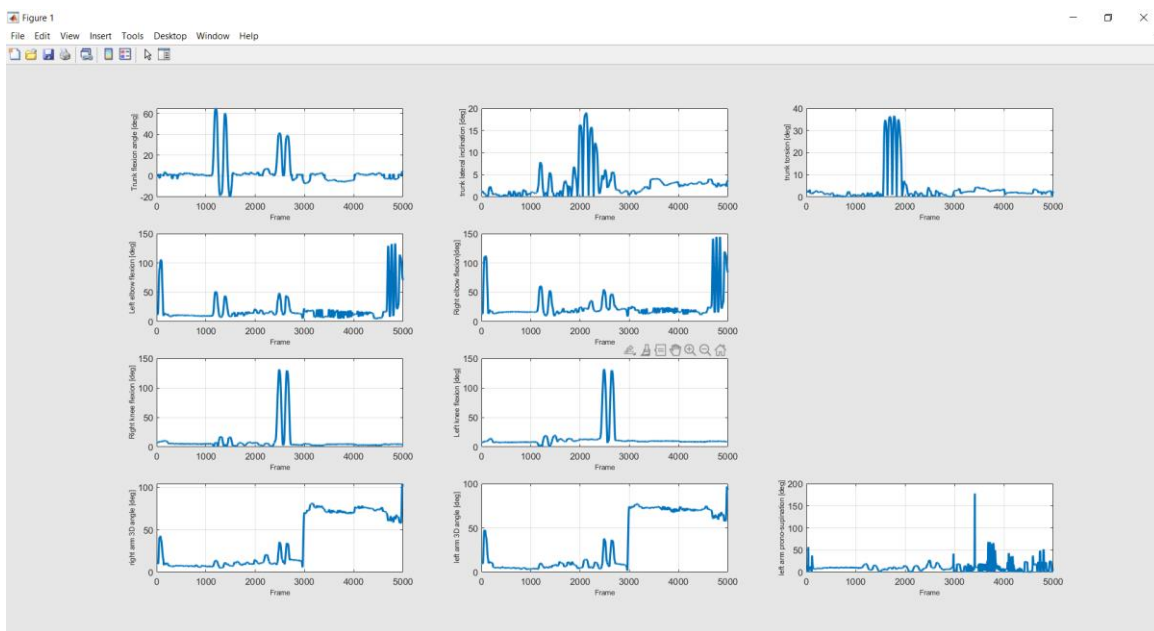


Figure 29 Example of recorded angles as function of time of a whole test

3.7 Calculate and visualize joint angle in desired frame – DEMO 6

```
{'6) Calculate and visualize joint angle in desired frame'}
```

Enter number: 6

Enter number of frame:

Choose angle from list:

trunk_flexion

trunk_lateral_inclination

trunk_torsion

rightarm_abduction

leftarm_abduction

rightarm_flexion

leftarm_flexion

rightknee

leftknee

rightelbow

leftelbow

rightarm_angle

leftarm_angle

leftarm_prono_supination

Enter name of joint angle:

Once that the trend of each angle is plotted against time it is useful to check the postures of those frame who seems particularly critical. By typing any frame of the recording and a name of the angle from the list drawn in MATLAB command window a figure of the posture can be visualized with the reference planes, axis, points and segments involved in the calculation of the angle. This function has been implemented to validate the results of the algorithm by comparing them with the ones obtained experimentally. Some figure of the outcome of the function is reported here as a demonstration.

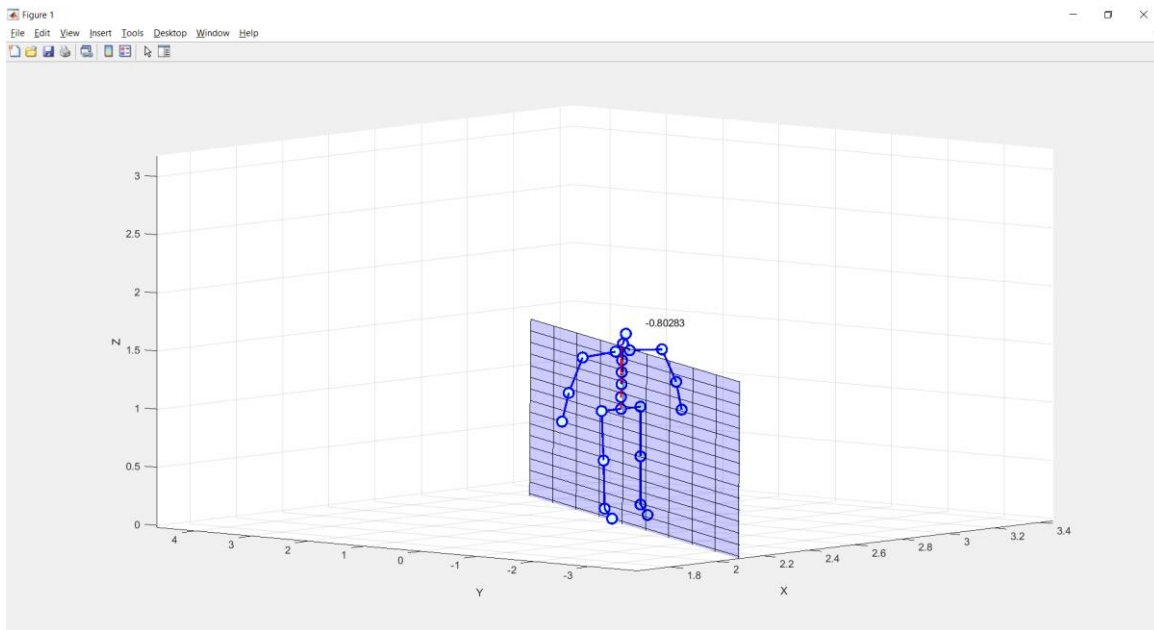


Figure 30 Example of trunk flexion segments visualization during upright position

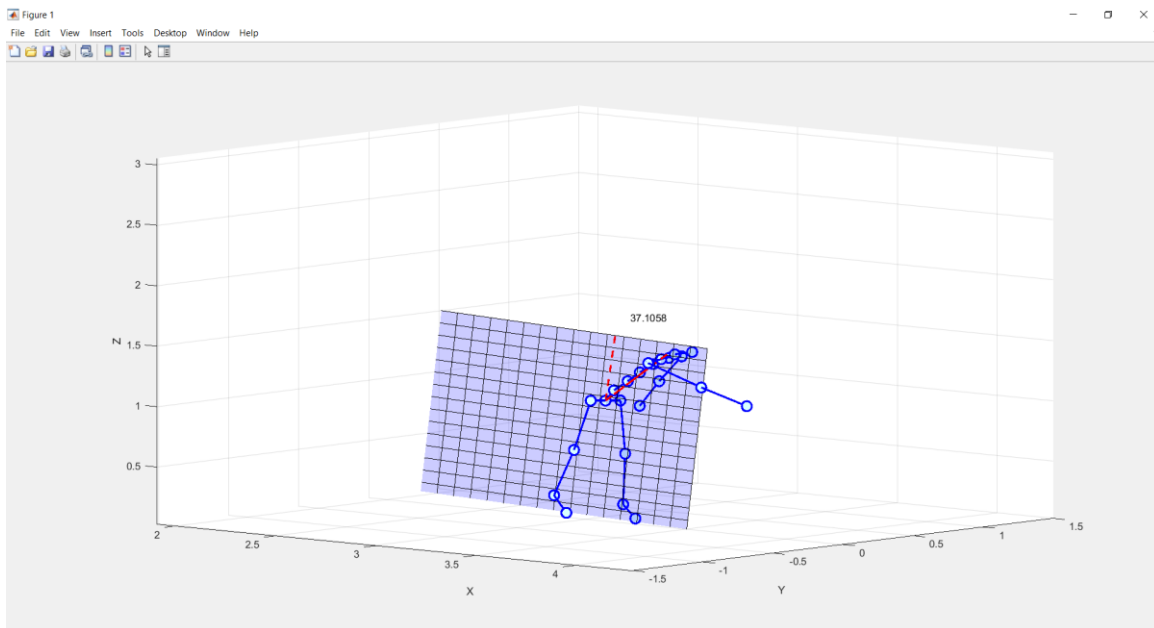


Figure 31 Example of trunk flexion segments visualization during far reach (100 %)

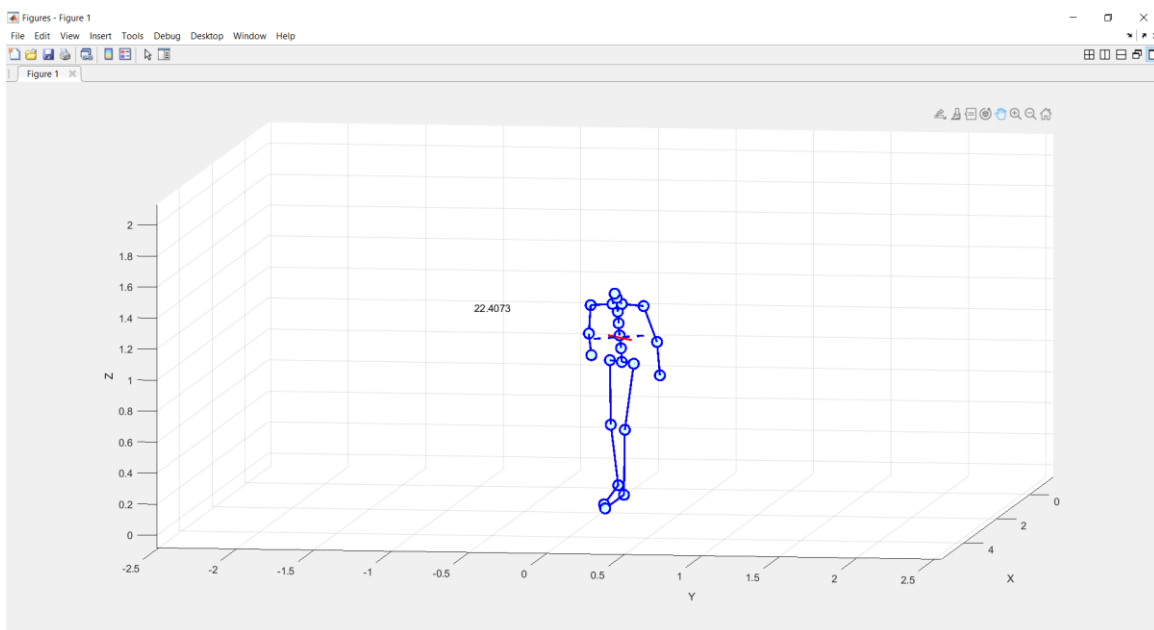


Figure 32 Example of trunk torsion segments visualization during close reach (40%)

3.8 Kinematic analysis – DEMO 7

A kinematic analysis allows to estimate the speed with which the postural angles vary as function of time (frames). The speed is simply obtained by making the first order derivative of the angle in the infinitesimal time window of 0.017 seconds that correspond to the reciprocal of the acquisition frequency (60 Hz). However, for our purposes it is quite redundant to have an instantaneous speed calculated on a punctual time frame of 0.017 seconds. For this reason, a Butterworth filter designed to have a frequency response as flat as possible in the passband has been applied. (See appendix for more details about Butterworth filters).

The outcome of the kinematic analysis is a plot of the instantaneous time derivative speed of the angles, instantaneous filtered speed of the angles, and the value of the angle as function of time (frame). In figure 33 the instantaneous time derivative speed is reported to highlight the filtering activity of the Butterworth filter.

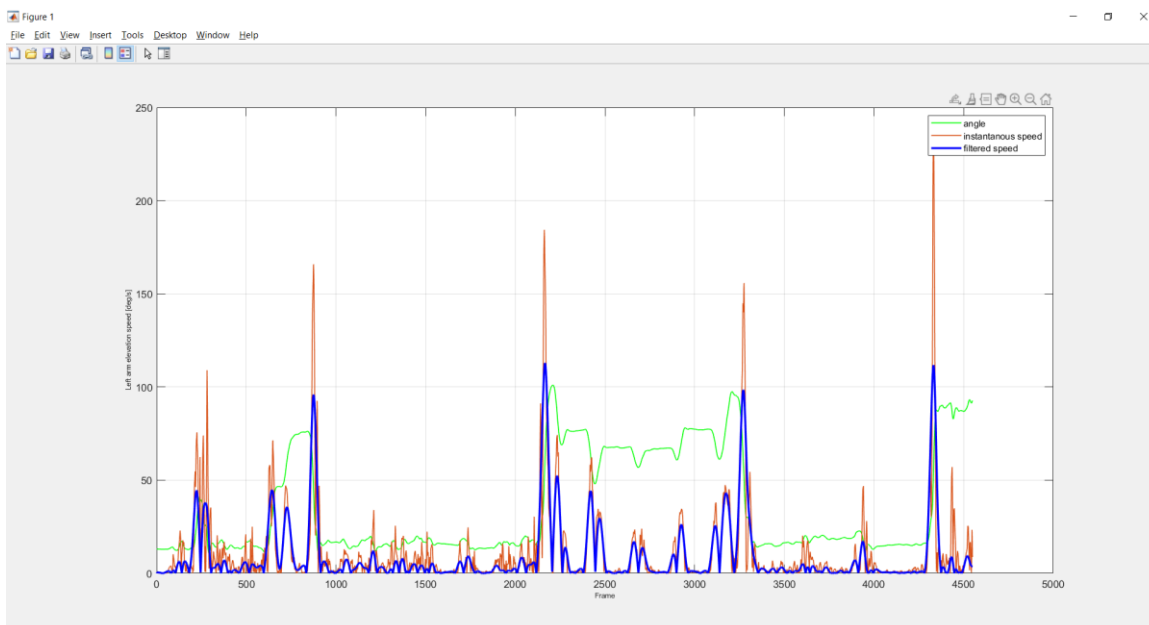


Figure 33 Left arm elevation angle (green), left arm elevation speed (red), filtered left arm elevation speed (blue) as function of time for a whole test recorded.

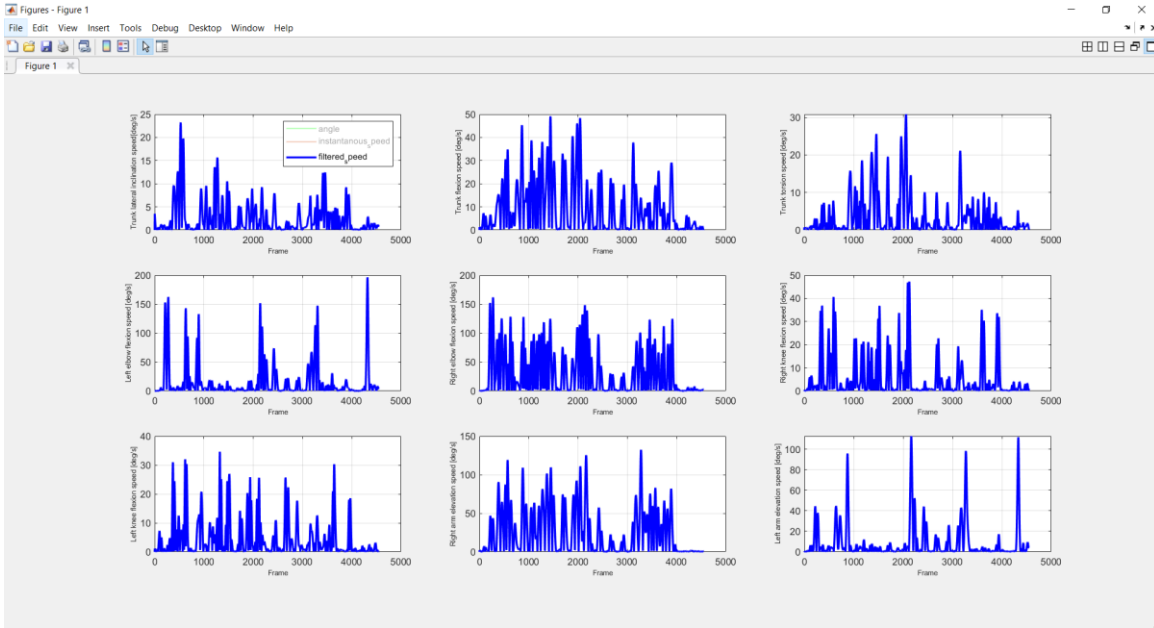


Figure 34 Filtered speed of variation of angles for a whole test recorded

The speed of each angle will be used as discriminant to distinguish between static and dynamic posture when we will set up the posture tracking algorithm. The posture tracking algorithm will only track posture recognized as static, hence whose speed is below a certain threshold.

4 Ergonomic Evaluation

4.1 Validation of joint angles

To extract a posture analysis with a solid scientific base to conduct an ergonomic evaluation we need to be sure that there is strong correlation between the angles “calculated” by the algorithm and the angles “observed” on the actor during the test. For the purposes of this project the angles calculated by the tool have been compared to the ones observed measured on camera during the execution of the test. The observed angles have been measured using KINOVEA, a very simple and intuitive video player for sport analysis. KINOVEA provides a set of tools to capture, slow down, study, compare, annotates and measure technical performances. The angles thus obtained are the ones that the ergonomic specialist would presumably estimates based on observational criteria if he would have to analyse the same test with present state techniques for ergonomic evaluation. Given such definitions of “observed” and “extracted” angles it is worth noting that none of the two is to be considered as the biomechanically correct one. The aim of the comparison is just to measure the differences between measurements performed with the two methods and point out how much can these differences affect the results of an ergonomic evaluation performed on the same test with the use of the tool and with observational criteria only. Bear in mind that the observational criteria applied by the ergonomic specialist are the ones described by European Regulations in terms of static working posture.

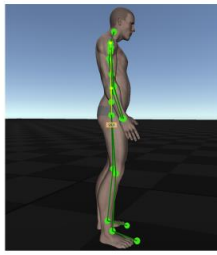
The results of two validation testing session are showed and commented below. Two validation sessions instead of just one have been organized to account for the error introduced by repeatability of acquired data, related mainly to the electromagnetic sensitivity of the sensors and variability introduced by calibration.

4.1.1 Validation Test – 001 – 14/10/2021

VALIDATION: TRUNK UPRIGHT



-1°



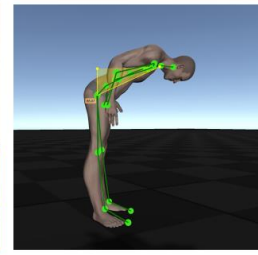
1°

$\Delta \approx 2^\circ$

VALIDATION: TRUNK FLEXION



59°



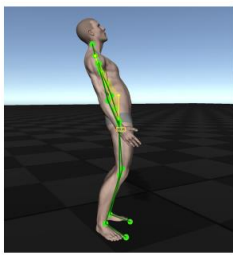
65°

$\Delta \approx 6^\circ$

VALIDATION: TRUNK EXTENSION



-20°



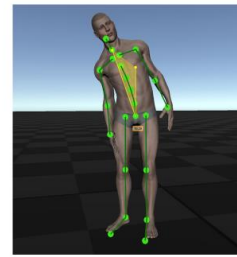
-20°

$\Delta \approx 0^\circ$

VALIDATION: TRUNK LATERAL INCLINATION



19°



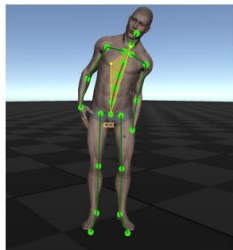
19°

$\Delta \approx 0^\circ$

VALIDATION: TRUNK LATERAL INCLINATION



19°



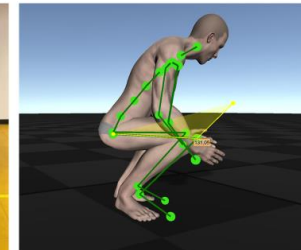
16°

$\Delta \approx 3^\circ$

VALIDATION: KNEE FLEXION



180°-39°=141°



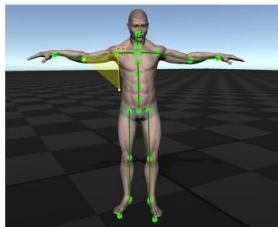
131°

$\Delta \approx 10^\circ$

VALIDATION: ARM ELEVATION



83°



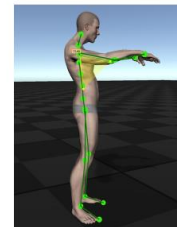
81°

$\Delta \approx 2^\circ$

VALIDATION: ARM ELEVATION



82°



73°

$\Delta \approx 11^\circ$

Figure 35 Comparison between observed and extracted angle in validation test 001

4.1.2 Validation test – 002 - 21/01/2021

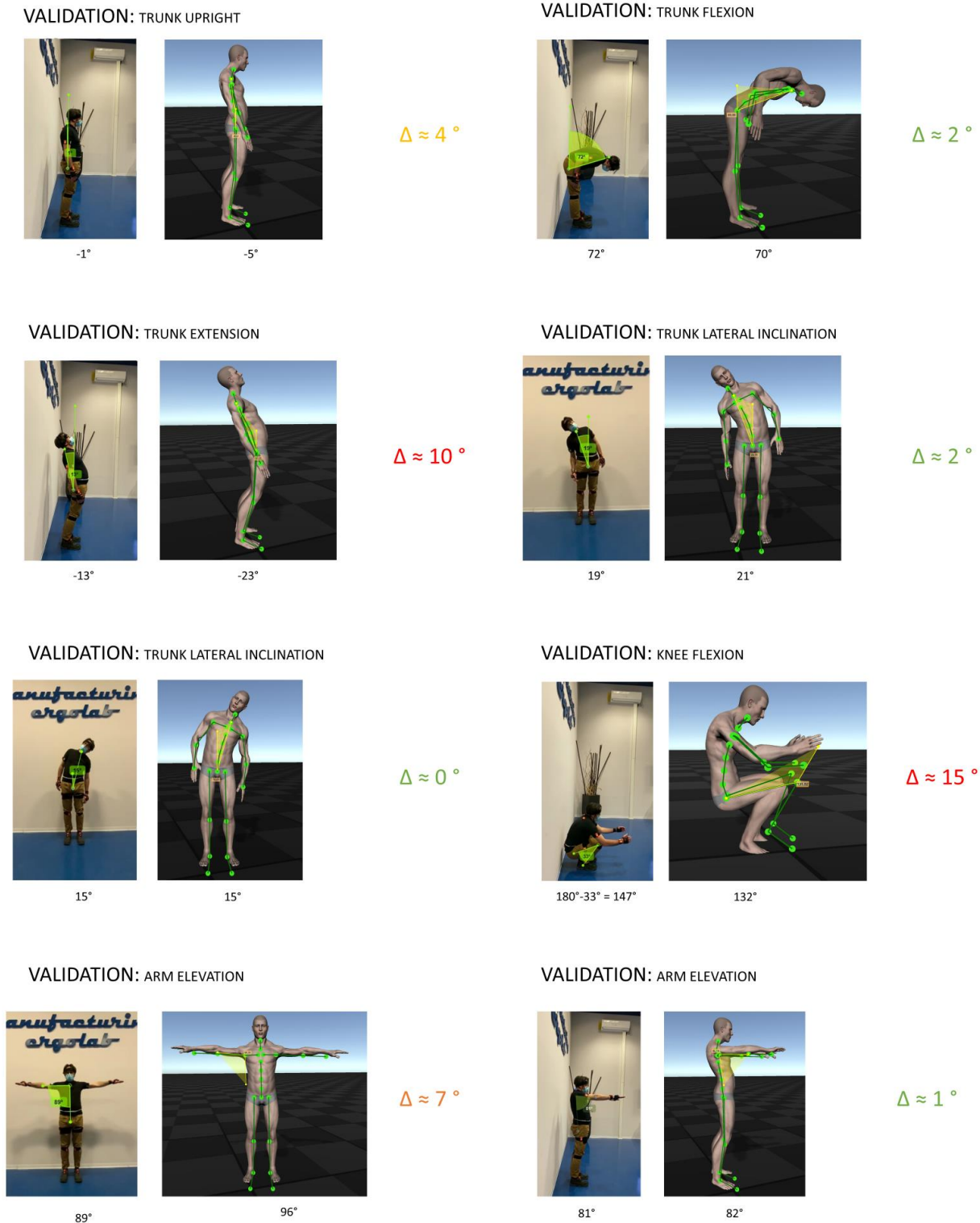


Figure 36 Comparison between observed and extracted angle in validation test 002

4.2 Comments

Validation test – 001 gave the lowest overall amount of differences between observed and extracted joint angles. This is probably due to better electromagnetic condition and better calibration during test execution. If so, it would mean that it is possible to achieve optimum correlation only in case optimal electromagnetic and calibration conditions. However, even in the second validation test – 002 differences oscillate in a reasonable range of tolerances. In the worst case regarding the knee flexion angle, the difference is in the order of 15° . This is an acceptable tolerance for the angle under consideration if we take into account that the observer does not recognize kneeling posture from a precise calculation of knee flexion angle but we assume that it recognizes it from knee flexion angles $> 100^{\circ}$. For what is concerned the trunk flexion angle, we noticed during the testing session that there is a strong dependence between the calibration and the angle recorded in neutral position. We would expect a very small trunk flexion angle in neutral position but that was not always the case. Frequently a slight backwards extension of the trunk was recorded in the order of 4-6 degrees. For this reason, it is reasonable to assume an offset of about 4 degrees to add up to the calculated angle in order to compensate for this effect. In regards of trunk torsion, trunk lateral inclination and arm elevation very good correlation is achieved with good repeatability of results.

In conclusion we can state that based on the outcomes of the validation testing sessions we expect that the results of the ergonomic evaluation performed by the tool should resemble with small tolerance the one performed by the ergonomic analyst with an accuracy which is dependent on the quality of the electromagnetic environment in which the test is performed and the quality of the calibration during the set-up phase of the sensors.

4.3 EAWS overview

Ergonomic risk assessment involves the measurement in terms of effort, posture and time of the following working motions:

- a) Upper limbs elevation (flexion, extension, adduction and abduction)
- b) Height of the hands relative to the head. Centre of the palm with respect to the line of the eyes
- c) Flexion, extension, rotation and lateral deviation of the neck
- d) Flexion, extension, torsion and lateral deviation of the trunk
- e) Elbow flexion, extension
- f) Elbow (forearm) pronation-supination
- g) Flexion, extension of the wrist and lateral (ulnar or radial) deviation
- h) Flexion, extension of the knees

The study of the influencing factors characterizing the level of risk of each of these movements and their interaction when combined within the same working activity are summarized in the section “Postures” of the so-called European Assembly WorkSheet (EAWS). The EAWS is a first level risk screening method for the evaluation of the biomechanical overload linked to work tasks that comprise high portion of cycle time spent in ergonomically awkward postures, high upper limbs repetitive movements, significant action force applied and manual material handling activities. EAWS respond to the need of evaluating the biomechanical risk in all its components in all body parts. It requires as input a number of information regarding the activity that must be analysed that normally have to be provided manually by the analyst. In this thesis an attempt to retrieve part of these information automatically starting just from Motion Capture data has been done trying to replicate the same logic as the one described in the EAWS applicator manual.

4.4 EAWS score determination – DEMO 8

The step that our algorithm must follow to retrieve correct results are:

1. Recognize and catalog symmetric working posture between 16 categories:
 - 1) Upright standing & walking slightly bent forward slightly bent backward
 - 2) Standing with no body support
 - 3) Bent forward (20°-60°)
 - 4) Strongly bent forward >60°
 - 5) Upright with arms at shoulder level
 - 6) Upright with arms above head level
 - 7) Sitting upright with back support slightly bent forward or slightly bent backward
 - 8) Sitting upright with no back support
 - 9) Sitting bent forward
 - 10) Sitting upright with arms at/above shoulder level
 - 11) Upright with arms above head level
 - 12) Kneeling or crouching upright
 - 13) Kneeling or crouching bent forward
 - 14) Kneeling or crouching with arms at/above shoulder level
 - 15) Lying on back or breast
 - 16) Climbing
2. Recognize and estimate the level of asymmetric working posture
 - a. Trunk torsion
 - b. Trunk lateral inclination
 - c. Far reach (arms extension)
3. Measure the amount of time spent consecutively in every posture (symmetric and asymmetric)
4. Neglect transition times between neutral posture, working posture and vice versa
5. Filter every working posture that does not remain still for at least 4 consecutive seconds (dynamic postures):

- a. In case the working posture last less than 4 sec but it is followed by its consecutive posture in the category list, the cumulative time between the two postures must be considered instead of the single interval before classifying it as a dynamic posture (see EAWS applier manual for more details)
6. Calculate the cumulative time spent in every static posture
7. Assign score to each of the symmetric body posture category involved in the activity based on the portion of cycle time spent in it
8. Assign score to each of the asymmetric body posture category based on the portion of cycle time spent in it and on the level of asymmetry

The sum of the score of the single body postures assumed during the work cycle will determine the biomechanical risk level induced by that activity. Details about score assignment can be found on the EAWS applier manual.

A traffic light evaluation is provided at the end (figure 37)



Figure 37 Risk level assigned to EAWS score result (MTM – EAWS applier user manual)

For what score assignment is concerned “FondazioneErgo” provides already a tool called “EAWS digital” that, provided as input the body posture category and the time spent in that posture, automatically calculate the final EAWS score for that task. The tool is then set up to track every posture assumed during the task, measure the time and generate an “.xml” file suitable to be fed to EAWS digital for the calculation of the final score and draw a summary of the postures involved during the task and how each of them contribute to the risk index identified by the activity.

Body posture	Trunk angle of asymmetry	Trunk incline	Far arms
			
			
			
			
			
			
			
			
			
			
			
			
			
			
			
			

Figure 38 EAWS list of body postures categories

5 Experimental testing

5.1 Reproduction of a true-like work-cycle in the lab

The first experimental campaign to validate postural angles calculation consisted just of basic posture not representative of real working conditions. A first experimental campaign to validate the posture recognition algorithm have been organized inside the workstation in order to verify the validity of the results in case of natural movements of the actor wearing the sensors. The environment used for the experiment was a real reproduction of a true assembly line workstation present inside the ERGOLAB of FCA manpower analysis department. The tasks to be simulated have been chosen so that to be significant from an EAWS point of view. This means that it has to include a good combination of mixed postures in order to verify that there is not interference between conflicting postures and that to each frame of recording during the task the EAWS code recognized by the algorithm is the same as the one we would expect the analyst to select in the traditional way of compiling the spreadsheet.



Figure 39 1:1 scale reproduction of an assembly line inside FCA ErgoLab (Torino, Mirafiori, Corso Settembrini C.16)

Task number one, to which we will also refer to as true-like test – 001, consisted of installing gaskets to doors' external perimeter.

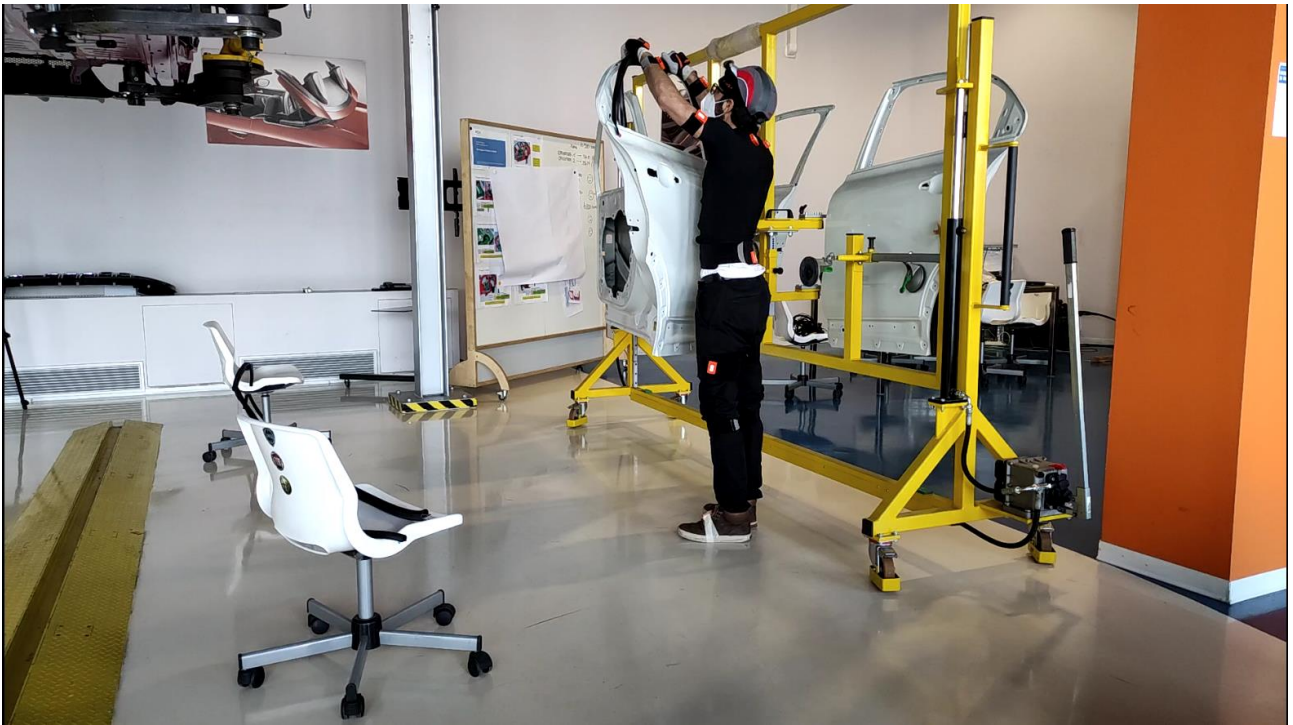


Figure 40 Applying gasket around the window frame



Figure 41 Applying gasket on the wheel arch



Figure 42 applying gaskets on the lower part of the door

As we can see from the figures the worker is forced to assume different kind of awkward postures. We expect in figure 40 to retrieve as output an EAWS code equal to 6 (arms above head level), in figure 41 EAWS code 3-4 plus moderate level of trunk lateral inclination and in last figure 42 EAWS code 12-13. Notice that, the time spent in each of these postures must be measured neglecting the transition times to achieve the reference posture based on the speed with which the angles vary and that in case the posture does not remain still for at least 4 consecutive seconds it should be discarded as dynamic posture and should not be taken into account in the calculation of the final score.

5.1.1 Results

The final score of the task with a summary of the postures recognized by the algorithm is showed in the following figure 43

The work content of one worker lasting 109,30 s has been analyzed. EAWS method in version E 1.3.5 2016-05-25 was used for analyzing.
















Evaluation					
Whole body			Upper limbs		
	Posture	78,5 points		Task	0,0 points
	+ Forces	0,0 points		+ Hand/Arm/Shoulder	0,0 points
	+ Manual material handling	0,0 points		+ Further factors	0,0 points
	+ Extra points	0,0 points		* Duration	6,5 points
	Total points	78,5 points		Total points	0,0 points
Body postures (78,5 points)					
	standing and walking upright, slightly bent forward/backward	EAWS rows 1	12,4 Seconds	0 points	
	bent forward (20-60°)	EAWS rows 3a	5,2 Seconds	1,9 points	
	bent strongly forward > 60°	EAWS rows 4a	3,6 Seconds	2,2 points	
	upright arms above head level	EAWS rows 6	32,0 Seconds	38,5 points	
	Arms at/above shoulder level	EAWS rows 14	19,5 Seconds	28,6 points	
Sums					
	Sum (static)		72,7 Seconds	71,2 points	
	Sum (not calculated, load/not static)		36,5 Seconds	1,0 points	
	Balancing difference		0,1 Seconds	0 points	
	Sum (total)		109,3 Seconds	72,2 points	
3D posture					
	Trunk angle of asymmetry	Duration:	4,4 Seconds	1,0 points	1,0 * 1 = 1,0
		Level of load:	15 °	1 points	
	Trunk incline	Duration:	16,3 Seconds	2,5 points	2,5 * 1 = 2,5
		Level of load:	15 °	1 points	
	Far reach	Duration:	5,1 Seconds	0,8 points	0,8 * 3,2 = 2,6
		Level of load:	81,7 °	3,2 points	
	Sum (3D posture)			6,1 points	

Figure 43 Door gasket task summary chart and score determination

The score of the task results in a particularly dangerous situation because we did not consider any recovery time. For our purpose of comparing the results obtained with the new method with the ones obtained in the traditional paper and pen way, this is an acceptable approximation because adding the recovery time would affect in the same way the score obtained with the two methods making just the calculation longer. In the following figures an example of the way the algorithm assigns EAWS code based on the recorded postural angles is showed.

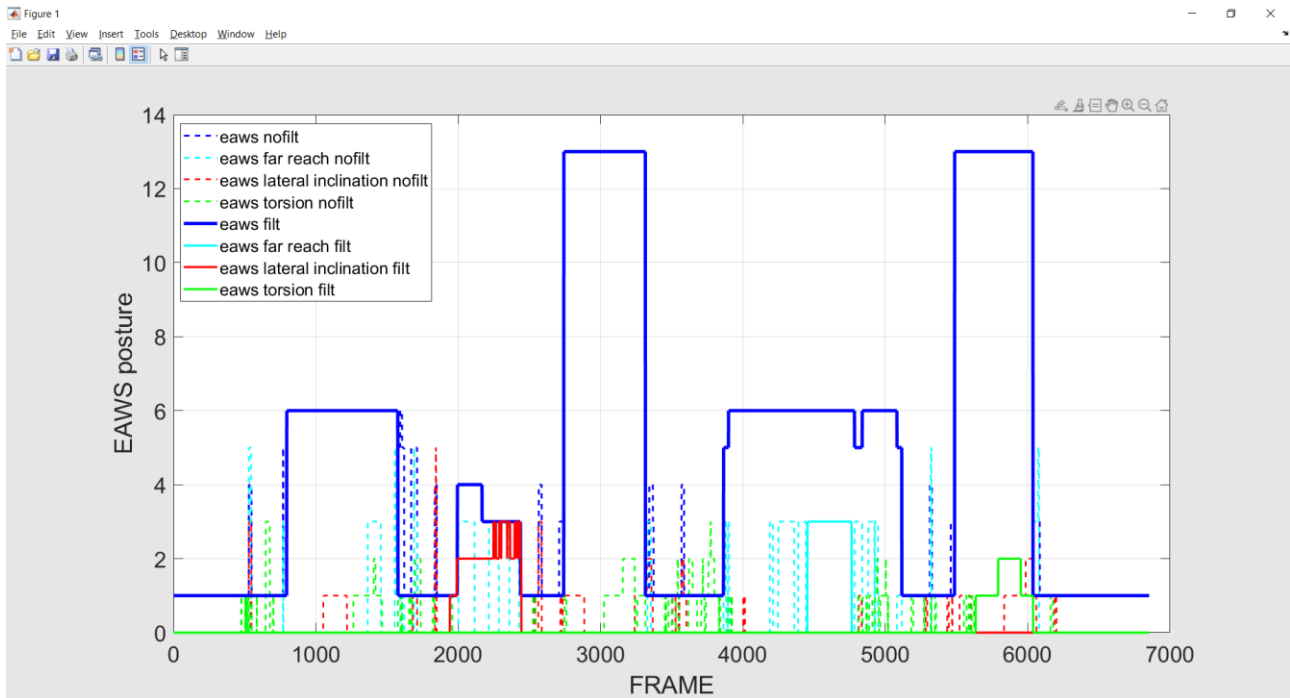


Figure 44 Posture tracking summary of true-like test 001 as function of time (frame)

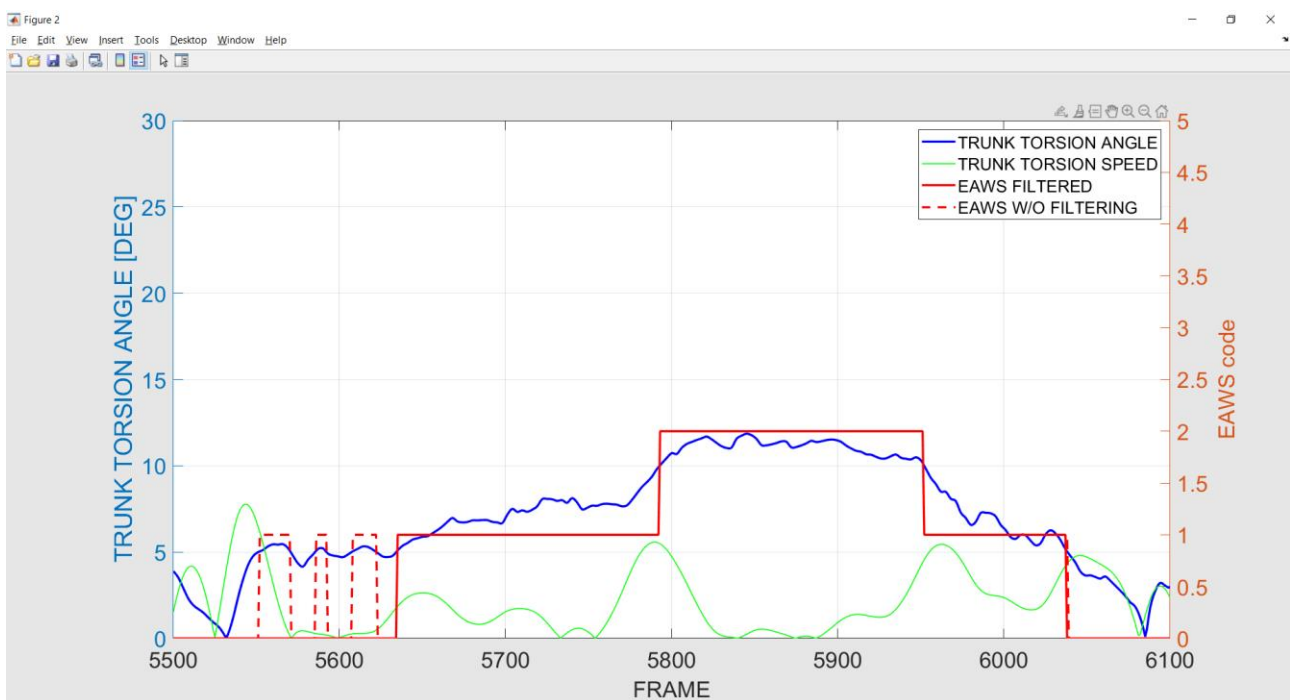


Figure 45 Trunk torsion posture tracking. Zooming in frame 5500 - 6100

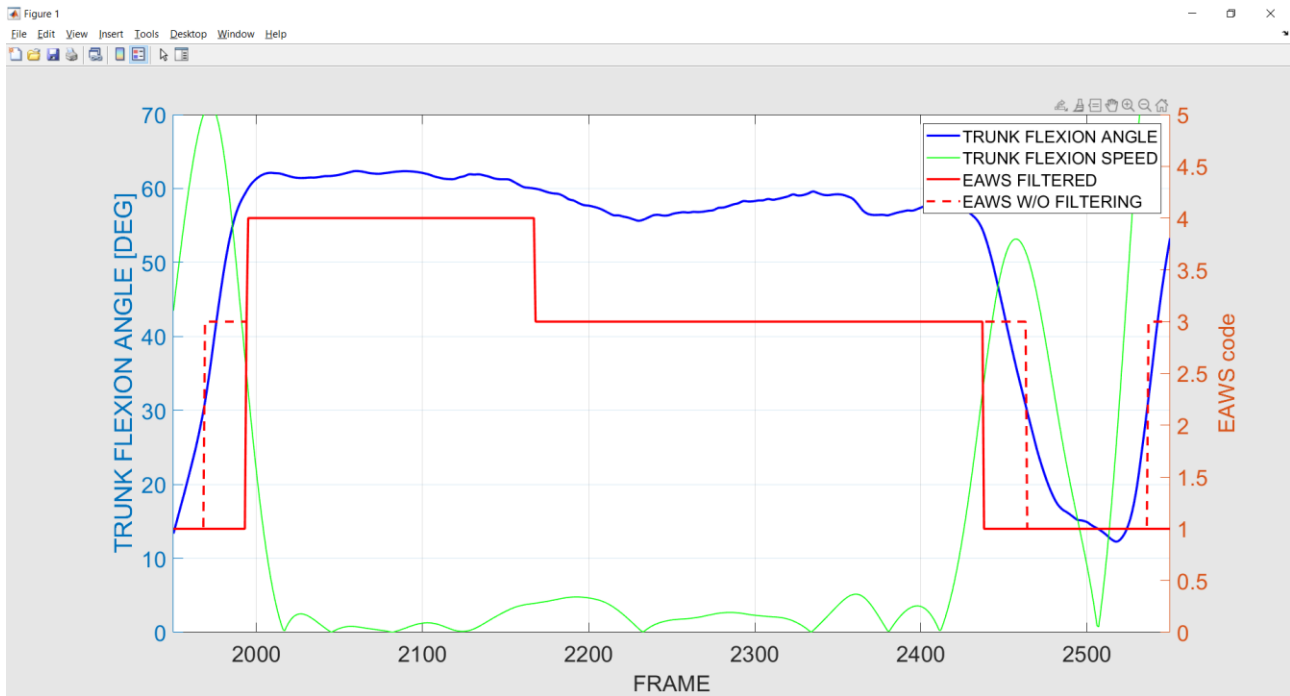


Figure 46 Trunk flexion posture tracking. Zooming in frame 1950-2550

Dashed lines indicate the posture that are recognized as dynamic either because the speed of variation of the reference angle is higher than the limit threshold or because the posture does not persist for at least 4 seconds. In both cases it should not be taken into account in the EAWS analysis.

5.2 Reproduction of a true-like work-cycle in virtual environment

During the manufacturing engineering and industrialization phase it is not always possible to access the production workstations to test new working activities that has to be implement in the foreseeable future. Manufacturing ERGOLABS are able to physically reproduce much of the tasks performed at the assembly line but not all them. This leads the Manpower analysis department to invest on new technology able to reproduce virtually the whole factory in a surprising accurate way. Thanks to these technologies it is possible to reproduce virtually any activity inside the production plant provided that the Computer Aided Manufacturing (CAM) scene is available. For courtesy of FCA we had available the CAM scenes of two workstations of FCA Melfi assembly plant. The task, to which we will also refer to as VR-test-005, consist of mounting the roof bars on top of a vehicle as it moves along the line.

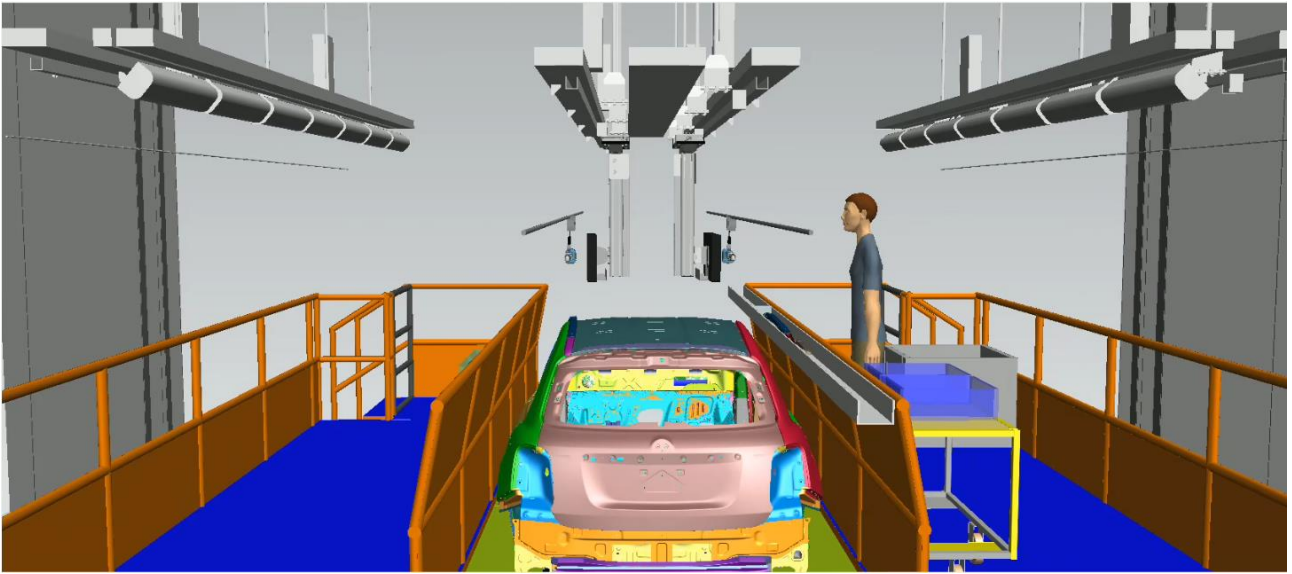


Figure 47 CAM scene visualized by the actor through the VR helmet as he performs the task

In this case the actor must wear both Motion Capture sensors and the helmet for virtual reality view to dive into the scene and move as if it is in the true workstation. From the point of view of the reproduction of the work-cycle, there is no reason to doubt that the approximation of motion is good enough except for the absence of the actual tools used during the activity (for example in this case we had to move the roof bars and handle an electric screwdriver whose weight cannot be considered negligible).



Figure 48 Actor wearing both VR helmet and Motion Capture sensors

5.2.1 Results

As we can see from figure 49, the most relevant postures assumed by the worker regard the trunk symmetry code 3 and asymmetry postures (trunk flexion, trunk torsion and lateral inclination). However, almost none of them are recognised as static therefore they are classified as not significant for the EAWS analysis (dashed lines). Still, some points are assigned to trunk torsion and lateral inclination as we can see from the summary chart of figure 50.

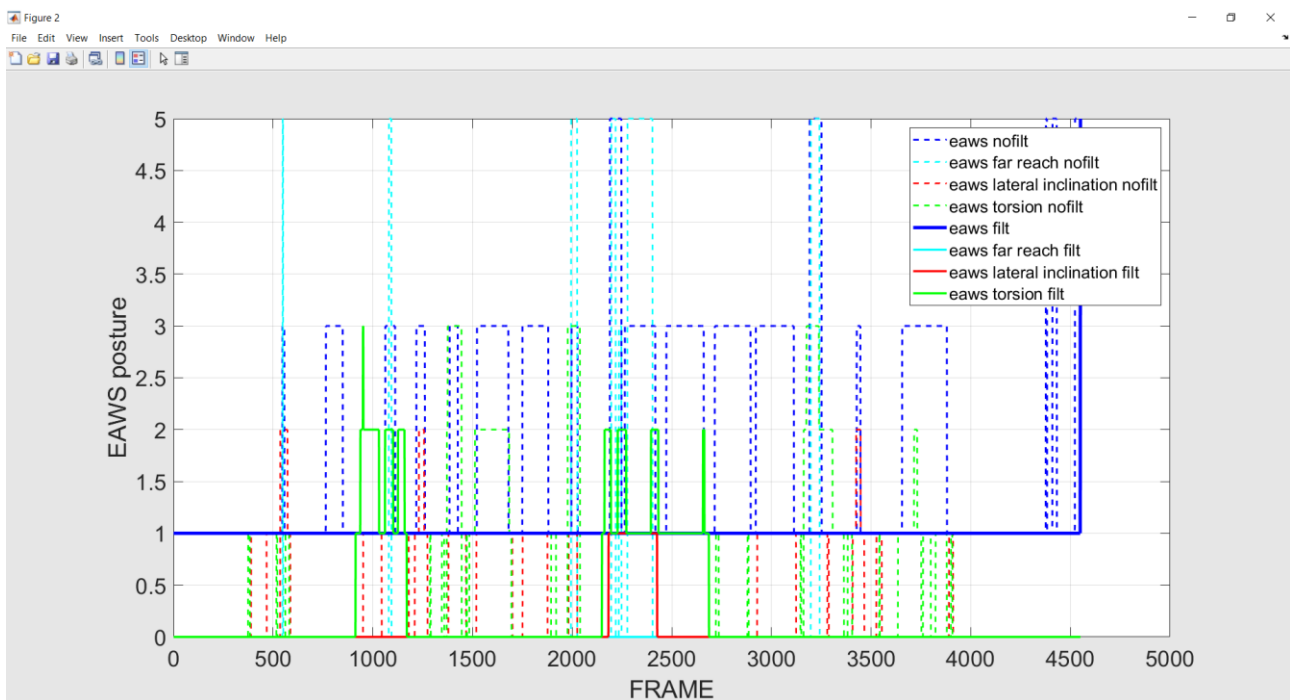



Figure 49 Posture tracking summary of VR Test 005 as function of time (frame)

The work content of one worker lasting 71,90 s has been analyzed. EAWS method in version E 1.3.5 2016-05-25 was used for analyzing.

Evaluation

Whole body



Posture

2,5 points

+ Forces

0,0 points

+ Manual material handling

0,0 points


+ Extra points

0,0 points

Total points

2,5 points

Upper limbs



Task

0,0 points

+ Hand/Arm/Shoulder

0,0 points

+ Further factors

0,0 points


* Duration

6,5 points

Total points

0,0 points

Body postures (2,5 points)




standing and walking upright, slightly bent forward/backward

EAWS rows 1

13,3 Seconds

0,4 points


Sums



Sum (static)

13,3 Seconds


0,4 points



Sum (not calculated, load/not static)

58,5 Seconds


1,6 points



Balancing difference

0,1 Seconds

0 points




Sum (total)

71,9 Seconds


2,0 points

3D posture



Trunk angle of asymmetry

not applicable



Trunk incline

Duration:

1,1 Seconds


Level of load:

15 °

0,4 points


1 points

0,4 * 1 = 0,4



Far reach

not applicable



Sum (3D posture)

0,4 points

Figure 50 Roof bar installation summary chart and score determination

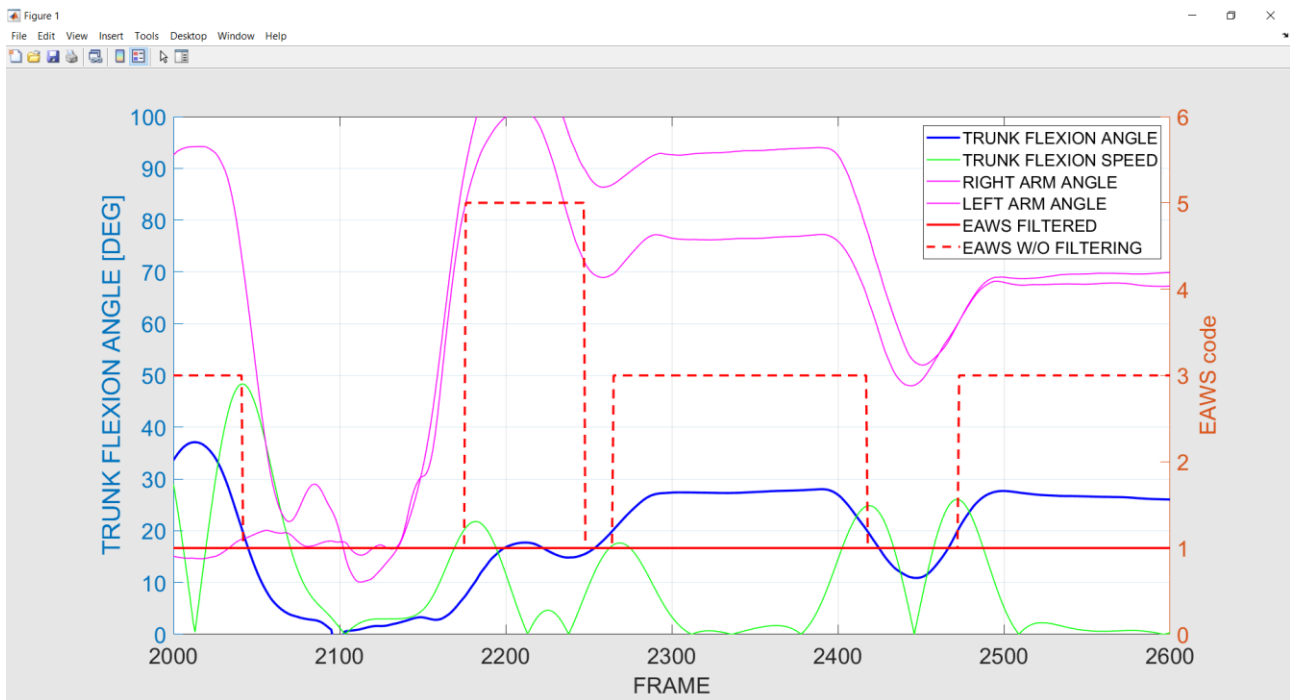


Figure 51 Arm elevation and trunk flexion posture tracking as function of time (frame). Zooming in frame 2000 - 2600

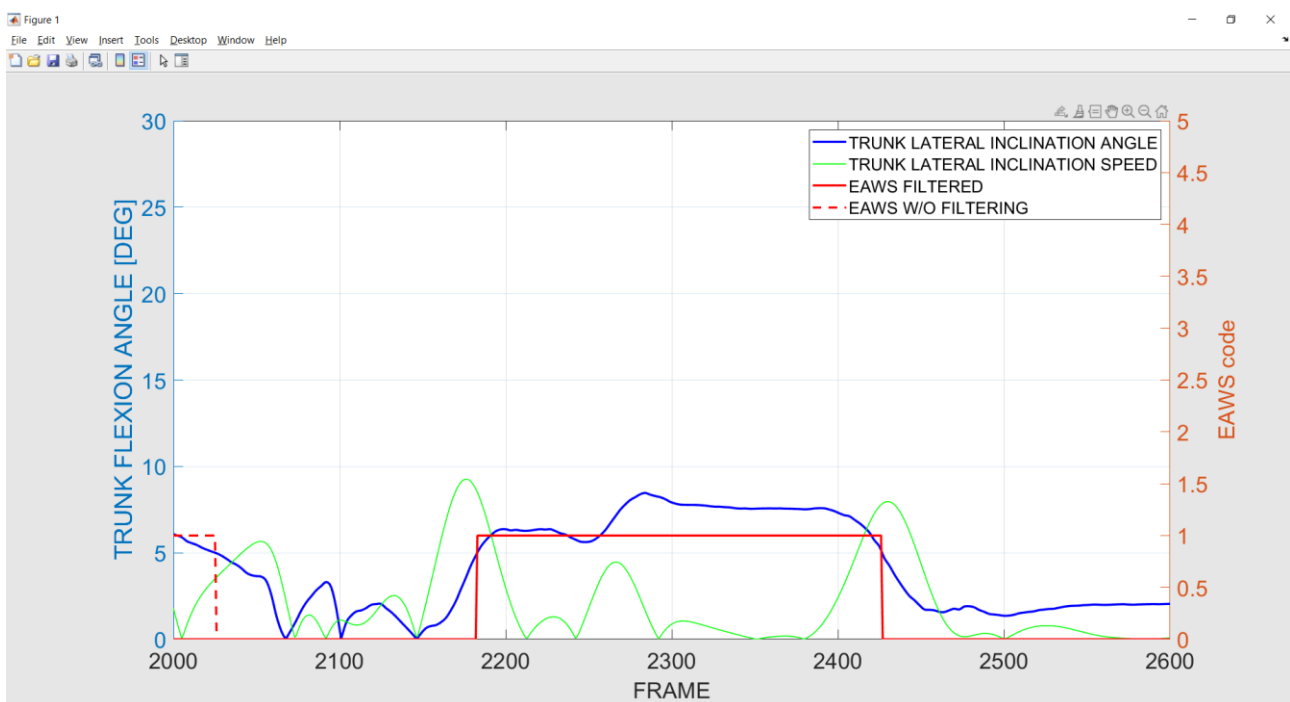


Figure 52 Trunk lateral inclination posture tracking as function of time (frame). Zooming in frame 2000 - 2600

5.3 Comparison with current methods of evaluation

The same tasks described above are now analysed according to the standard “paper and pen” procedure with which EAWS is nowadays still estimated. The idea is to compare the results and understand how robust is our machine in distinguishing static postures and assign a level of severity to each of them, compared to human interpretation of the same task.

5.3.1 True-like Test- 001 “paper & pen”

cycle time = 114 sec

28 sec : arms above head level → 33 POINTS

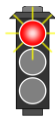
8 sec : slightly inclined laterally → $1 \times 2 = 2$ POINTS

8 sec: strongly bent forward → 5 POINTS

24 sec: kneeling or squatting bent forward → 20 POINTS

saturation time = $114 - 28 - 8 - 24 = 54$ sec → 1 POINTS

SUM OF STATIC POSTURES = 61 POINTS



5.3.2 VR - Test-005 “paper & pen”

cycle time = 75 sec

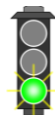
16 sec : slightly bent forward with suitable support → 7 POINTS

8 sec : slightly inclined laterally → $1 \times 2 = 2$ POINTS

8 sec: slightly twisted → $1 \times 2 = 2$ POINTS

saturation time = $75 - 16 = 59$ sec → 2 POINTS

SUM OF STATIC POSTURES = 13 POINTS



5.3.3 Comments

In true-like Test – 001 we get in both cases a quite remarkable red light with more severity identified by the tool than by human interpretation of the task. The most relevant differences are related to the kneeling & squatting posture. In this case the tool read an elevation arm angle higher than 90° and classify the posture with EAWS code 14 (kneeling or squatting with arms at/above shoulder level). To the human eye instead it stands out that the most representative posture in this case is the one corresponding to EAWS code 13 (kneeling or squatting bent forward) which is less severe with respect to code 14. Therefore, the score calculated by the tool indicate a more dangerous situation than the score obtained by observational criteria. Provided that the angle recorder by the tool are correct, we can state that human eye is not capable of perceiving 3D arm elevation angle especially in case of mixed posture (as this one in which the actor is kneeling visibly bent forward). The choice of code 14 instead of 13 is therefore correct according to the conservative principle of the worst-case scenario.

In VR- Test – 005 it seems like we have the opposite trend. The tool underestimates the score with respect to human interpretation of the task. As we already mention, almost all the movements of the actor are classified as dynamic by the tool and none of them contribute to the final score of the task. If we stick to the math, the measured time of the static posture, neglecting transition times and considering the varying speed of the angles, tells us that almost the whole task is indeed performed assuming dynamic movements and none of the reference posture remain still for at least 4 seconds. Human interpretation of the task instead assigned 16 cumulative seconds to EAWS code 3 (slightly bent forward) whose cost is 7 POINTS. Even though this difference does not impact the final outcome of the analysis, that is a green light in both cases, it is worth considering the implementation of a higher tolerance for the principle that discriminate dynamic from static postures. EAWS applicator manual imposes 4 sec as discriminant, that means 240 frames. To be sure not to discard any static posture that may increase the severity of the task we could set 3,5 seconds thresholds, that means 210 frames (60 Hz recordings). In doing so the analysis retrieve as output 11 POINTS instead of 2,5 approaching the 13 POINTS calculated by means of observational criteria only.

6 Conclusions & future perspectives

As already mentioned, Motion Capture techniques available on the market up to now are mostly addressed to the videogame industry and animation cinematography. It means that great effort must be spent in make them suitable for ergonomic analysis without giving up too much accuracy of calculation. The proposed definition of joint angles is based on the guidelines provided by European Regulations in terms of static working posture. During the validation testing session, the calculated joint angles proved to be strongly correlated to human body movements. As a matter of fact, the coherence between movements and joint angles is kept within reasonable limits even in case of awkward mixed working postures. This is critical in measuring the robustness of the algorithm for posture recording. The first milestone that we encountered was then the verification of the reproducibility of working postures in coherence with the norms with reasonable level of tolerance.

Once that the correlation among data e movements is estimated and judged sufficiently good the second milestone is the definition of the posture tracking algorithm. The most critical aspect here was to establish a robust hierarchy among the postures to be assigned. As a matter of fact, there could be situations in which two working posture coexist but only the most representative for the task must be assigned. The ergonomic specialist knows always which one is the most representative, different is the case in which a computer must learn every possible combination of coexisting posture to define which one is the most representative in every situation. In the tests we have performed to validate the posture tracking algorithm the choice of the posture proved to be always the same as the observer would have chosen even in the most articulated work tasks.

The last aspect we took care of was the determination of the EAWS score of the section posture. In doing so the exact same rules written in the EAWS applier manual have been translated in computer language based on the calculated angles and speeds. The most critical part was to discriminate dynamic motions postures from the calculation of the final score. In some cases the algorithm proved to retrieve a less severe analysis than an ergonomic specialist would have done. This is because of a more rigid application of the rules based on measured data without knowledge nor interpretation of the task on its own. We have seen that it is

possible to apply less stringent conditions in the definitions of postures in order to retrieve a more conservative analysis and always be on the safe side of the mistakes.

Ergonomics comprehends many aspects of the working activity. Static posture assessment is probably of major concern because it has the biggest impact in musculo-skeletal disorders but it is not the only factor contributing to professional diseases. A comprehensive ergonomic analysis should include also methods for the evaluation of neuro-muscular and tendon disorders mainly caused by dynamic loads. The application developed up to now is ready to be used to analyse static working postures and evaluate the risk related to static loads. The next steps are to integrate functions able to elaborate additional information about the task to carry out a dynamic actions analysis including the application of forces. Such information will have to be provided preferably by means of sensors so that to leave to the user the least possible amount of responsibility and expertise in conducting the analysis as well as to speed up the entire validation process of the activity.

7 APPENDIX

7.1 Quaternions

The term quaternion indicates a quadrinomial expression made of a real part, q_0 , and an imaginary part made of three coefficients q_1 q_2 q_3 multiplied respectively by the imaginary units i j k . The following properties holds:

$$q_0 + q_1i + q_2j + q_3k$$

$$i^2 = j^2 = k^2 = -1$$

$$i \cdot j = k$$

$$k \cdot i = j$$

$$j \cdot k = i$$

$$j \cdot i = -k$$

$$i \cdot k = -j$$

$$k \cdot j = -i$$

In literature, often, quaternions are referred to as a real part and a vector. They are commonly used in three-dimensional computer graphic and computer vision for calculation involving rotations in space. In this thesis they have been used to obtain transformation matrixes with which to construct marker's local reference systems starting from the global ref system to which all markers location is referred to. The function `quatrotate` used in DEMO 3 apply the following formula for every marker frame by frame:

$$global_ref_sys = \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$local_ref_sys = \begin{bmatrix} v'_x \\ v'_y \\ v'_z \end{bmatrix} = \begin{bmatrix} 1 - 2q_2^2 - 2q_3^2 & 2(q_1q_2 + q_0q_3) & 2(q_1q_3 - q_0q_2) \\ 2(q_1q_2 - q_0q_3) & 1 - 2q_1^2 - 2q_3^2 & 2(q_2q_3 + q_0q_1) \\ 2(q_1q_3 + q_0q_2) & 2(q_2q_3 - q_0q_1) & 1 - 2q_1^2 - 2q_2^2 \end{bmatrix} \cdot \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} + marker_location$$

7.2 Butterworth filters

Butterworth smoothing filter is often referred to as a maximally flat magnitude filter. It is applied to the differences among two successive frame's amplitudes (time derivative in discrete time). MATLAB function `[a b]=butter(order,cutoff_freq)` compute the transfer function coefficients of an n^{th} order lowpass digital filter with normalized cut-off frequency. The transfer function is then applied to raw data by means of the `filtfilt` zero phase digital filtering function. Zero-phase filtering helps preserve features in a filtered time waveform exactly where they occur in the unfiltered signal. Zero-phase filtering reduces noise in the signal and preserves the QRS complex at the same time it occurs in the original signal. Conventional filtering reduces noise in the signal but delays the QRS complex which is not ideal in case we need correlation between data and time.

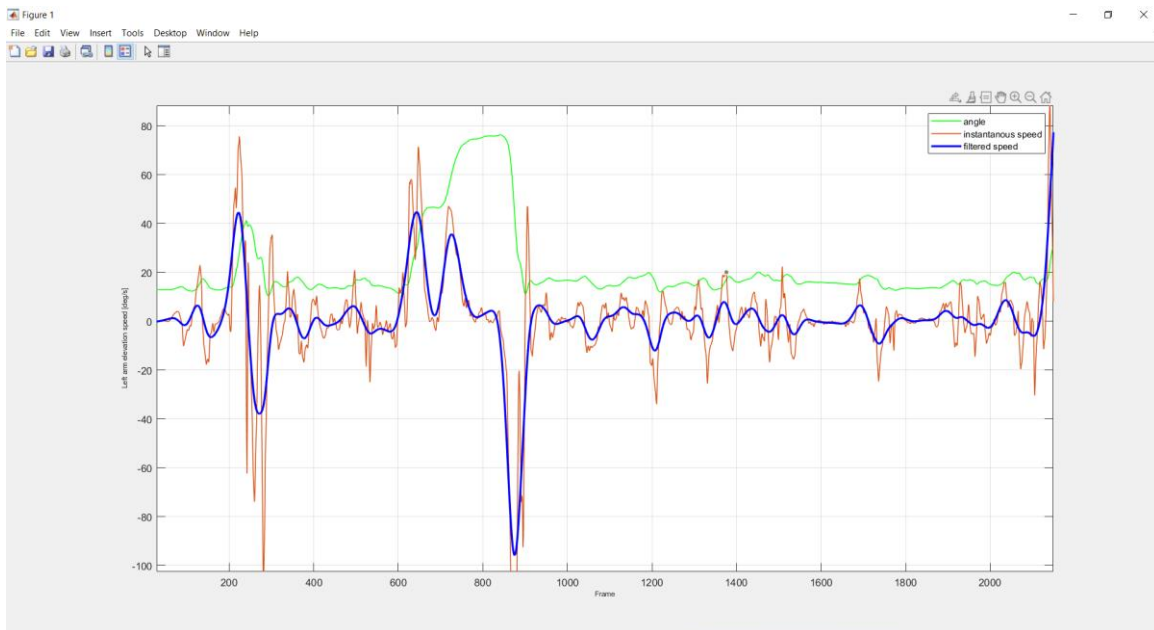


Figure 53 Left arm elevation angle (green), left arm elevation speed (red), filtered left arm elevation speed (blue) as function of time for a whole test (cutoff frequency = 0.03)



Figure 54 Left arm elevation angle (green), left arm elevation speed (red), filtered left arm elevation speed (blue) as function of time for a whole test (cutoff frequency = 0.017

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Sitography

https://it.mathworks.com/videos/modelbased-design-of-safety-relevant-industrial-control-software-123648.html?elqsid=1603633513201&potential_use=Student

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Mocap_toolbox (https://www.mathworks.com/matlabcentral/fileexchange/62513-mocap_toolbox), MATLAB Central File Exchange.

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*To myself,
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