# POLITECNICO DI TORINO

Master's Degree in Biomedical Engineerign



Master's Degree Thesis

# Design and development of a postural prediction system for Digital Human Model in 3D virtual work-station assessments

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# Summary

Awareness of how important it is to preserve employees' physical and mental health has grown in the past decades. Creating a safe and ergonomic work environment has become one of the main concerns of engineers and researchers nowadays. The integration of new technologies into the workplace, such as artificial intelligence and virtual and augmented reality, to design a human-centered work environment is investigated continuously. Virtual reality is the most widely used technique in the latest ergonomic assessment approaches in which human-workstation interaction can be simulated using digital human models (DHM) while the workstation can be imported using CAD models. The applications developed so far are quite sophisticated and need extensive training. In this frame, the proposed thesis aims to implement a simple-to-use, low-training system for the ergonomist, in which the DHM is animated by inverse kinematics. The postural prediction system predicts the behavior of a DHM with different anthropometric percentiles within a virtual workstation. To implement the model, the Unity3D engine and an inverse kinematic tool, the Final IK, were used. To predict an ergonomic posture the Final IK was supported by postural rules.

Xsens Awinda technology was used to record a motion capture session and evaluate the input parameters for the postural prediction system. The user replicates a work task, on-site or in a virtual environment. Hands and feet positions and rotations, as well as head rotations, are extracted.

Alternatively, if a motion capture session is not feasible, the user can insert the target's coordinates or move them via keyboard commands. The user has the opportunity to move the end effectors (hands and feet) but also the hips, shoulders, and pelvis. This is useful either to assess a specific posture or to fine-tune the posture erroneously predicted by the system.

If a virtual workstation is loaded into the Unity scene, the system is also able to detect possible collisions with objects and use this information to adjust the predicted posture accordingly.

The testing phase involved the recording of several motion capture sessions. The user was always different in each session to represent different percentiles and highlight critical issues in the prediction system. The experimental phase confirmed the advantages of introducing postural rules and constraints imposed by the workstation to obtain more realistic postures.

This project confirms what emerged from the related literature review: these applications are useful to highlight any technical issues caused by workstation organization, before producing any physical prototypes. Thus, allowing for faster intervention in the workstation design while saving time, cost, and resources.

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# Acronyms

#### $\mathbf{AI}$

Artificial Intelligence

#### IoT

Internet Of Things

#### $\mathbf{VR}$

Virtual Reality

#### $\mathbf{AR}$

Augmented Reality

#### CAD

Computer Aided Design

#### $\mathbf{CAM}$

Computer Aided Manufacturing

#### **MSDs**

Musculo Skeletal Diseases

#### DHM

Digital Human Model

#### 3DSSPP

3D Static Strength Prediction Program

#### RULA

Rapid Upper Limb Assessment

#### REBA

Rapid Entire body assessment

#### EAWS

Ergonomic Assessment Work-Sheet

#### MTM

Methods-Time Measuremen

#### CAVE

Cave automatic virtual environment

#### $\mathbf{F}\mathbf{K}$

Forward Kinematics

#### IK

Inverse Kinematics

#### FBBIK

FullBodyBiped IK

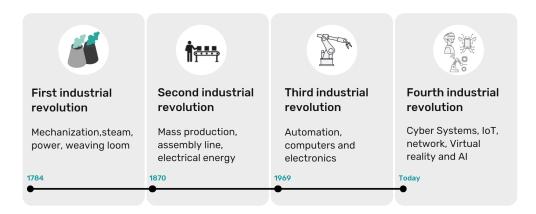
# Chapter 1 Introduction

In recent decades, the entire industrial world has to face the fourth industrial revolution due to the introduction of new technologies in the workplace. The industrial revolutions have always been strongly influenced by the discovery of new technologies. In fact, the first industrial revolution allowed mechanization through the use of water and steam power; in the second industrial revolution instead, the discovery of electricity allowed mass production and the creation of the first assembly lines. Computers and automation are introduced during the third industrial revolution often known as the digital revolution [1]. In some aspects, the fourth industrial revolution is considered as a continuation of the third one, since it enhances already integrated technology, through intelligent and automatous systems powered by data and machine learning [2].

## 1.1 Industry 4.0

When we talk about the fourth industrial revolution we also refer to the term Industry 4.0: this concept first appeared in 2011 at the Hannover Fairground [3] and it's now one of the most discussed subjects in manufacturing technology. The purpose of this initiative is to reinvent industrial manufacturing through digitalization and usage of new technology such as:

- Artificial intelligence (AI);
- Use of the internet and IoT;
- Integration of technical processes and business processes in the companies;
- Virtual and augmented reality.



**Figure 1.1:** Industrial Revolutions Timeline: The first industrial revolution began in the late 1700s with the introduction of steam engines. Over the next few centuries, manufacturing processes became increasingly automated allowing for mass production. With the advent of the fourth industrial revolution, production systems are becoming even more efficient than before

The basic concept of artificial intelligence is inspired by human learning models because the algorithms try to recreate the autonomous learning and adaptation capabilities. Machine learning algorithm is one of the most spread method, it is able to improve and adapt thanks to user's experience and that's why it is mostly used in social media such as Facebook, Instagram and Pinterest but also in different fields like e-commerce, engineering solution, health-care and medical.

The acronym IoT stands for "InternetOfThings" and it refers to radios, sensors, actuators, mobile phones, etc... All this items are active participants in business because they are able to interact by exchanging data [4].

Virtual Reality (VR) is a technology in which the real world is completely replaced by a virtual one. The user has the chance to interact with the virtual world and to live experiences with high sense of immersion. Augmented Reality (AR), on the other hand, is used to add information in the real world by offering enhanced experiences.

With the introduction of these new technologies, the terms of smart factory and virtual manufacturing became more and more relevant. Virtual manufacturing comprehends all those technologies that allow to optimize a production line, for example CAD (computer-aided design), CAM (computer-aided manufacturing) software, 3D mathematical simulation and modeling software, VR, and AI. The introduction of these technologies affects all the steps of manufacturing process. Product concepts such as ergonomics and functionality can be checked and validated using virtual environment during the initial design phase. A virtual environment offers you the possibility to interact in real time with the object of interest, leading to much more

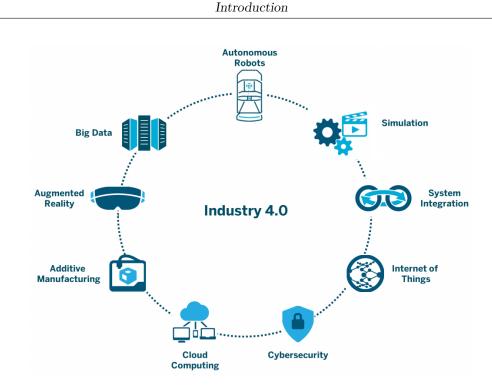


Figure 1.2: Industry 4.0 Technologies, source: [5]

realistic analysis and with more reliable results. Validation and manufacturing activities can be accomplished virtually before being physically implemented in the real world aiming to a maximization of the production efficiency. This is possible by reducing or avoiding unnecessary, complex or expensive functionalities. Production features like procurement, manufacturing, assembly, testing, distribution, delivery, assistance, and repair services can be optimized in advance and gained increasingly stringent requirements in terms of time-to-market, costs, quality, customization, reliability and safety. The main steps in the production process are described in the figure 1.3 comparing the classical approach to the virtual one.

With a traditional approach, subsequent to the CAD design phase, there is the physical implementation of mock-ups by-passing the simulation phase in virtual environment. However, if the results are not satisfactory, the modification and reorganization phase takes time because new mock-ups have to be made. Instead, the processes of validation are simplified by using virtual simulations because the virtual simulations allow to reveal any possible problem of the model before the physical mock-ups are realized. This leads to fast intervention of modification shortening a lot time and costs of validation [6]. Both productivity and operator's well-being in the manufacturing processes must be evaluated as two complementing components throughout the validation phase, and not as two distinct aspects.

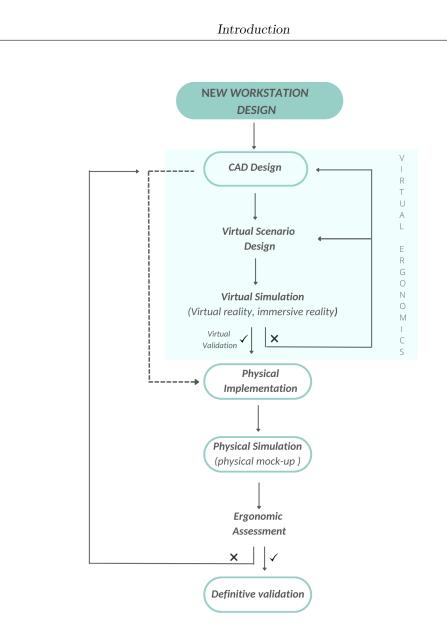


Figure 1.3: Development process in Virtual Manufacturing environment

Smart factories are defined as companies that are able to fully exploit all the potential of more innovative technologies. Giving up the classical industrial production pipeline and applying all principle of Industry 4.0 with the result of a system in which all processes are fully integrated. Smart factories have a lot of benefits in the logistics optimization of the production chain because there is the possibility to access to the real-time data making better and faster decisions. In fact, companies who invest in Industry 4.0 solutions claim a decrease in time-to-market for new items, as well as a considerable reduction in costs and a more responsible consumption of natural resources and energy. The author (Rojko, 2015) assume that a smart factory may report a decrease of cost about 10-30%, logistic costs about 10-30% and quality management costs about 10-20%.

The ever-increasing presence of these new tools in the industrial environment has certainly enabled the creation of more flexible and efficient production environments but on the other side, has also increased the complexity of using this instrumentation. Therefore, an increasingly important role is played by the training of the employees who will use these tools as well as the creation of safe workstations that guarantee the mental and physical well-being of workers. This last point has not to be underestimated, in fact « *Prevention is no longer just a word. Industrial businesses today now understand that the health and safety of their workers is a major component of financial success, like total quality, productivity and cost reduction. A healthy business is now one in which OHS^1 is regarded as an imperative » (Badri et al. 2018).* 

A well-organized workstation that is able to satisfy all the physical needs of workers is indispensable to a successful production, to meet these requirements it may be useful to use ergonomic approaches in order to have human-centered workplaces [9].

In the context of industry 4.0, the evaluation of the workstation can be achieved in early design phases by using virtual or augmented reality to recreate accurate simulations, in this cases we refer to Virtual Ergonomics [10] where the term ergonomics indicates the scientific discipline interested in understanding the interactions between humans and the other components of a system.

## 1.2 Ergonomics

Ergonomics is a word descended from the Greek " $\epsilon\rho\gamma\sigma\nu$ " meaning work-action and " $\nu\sigma\mu\alpha$ " meaning law-rule from which it derives the meaning of ergonomics as law of the job [11].

Is a discipline that originated in the United States around the 20th century when first research on the impact of working conditions on employee health and performance began [12]. Nowadays ergonomics refers to the interaction of the person with the surrounding environment, this definition was given by K.F.H.Muller in 1949. The following three factors should be considered in characterizing human-environment interaction:

1. The worker assigned to the performance of a specific task, considered both in

<sup>&</sup>lt;sup>1</sup>Occupational health and safety (OHS) is a program which aim is to improve workplace health and safety standards.

a physical sense (anthropometric characteristics, biomechanical aspects, etc.) and in a cognitive sense (mental load induced, social interactions, etc...);

- 2. The machine defined as the equipment or the instrument used to perform the assigned task;
- 3. The environment as the place in which the work is done, including the layout of the workstation.

Thus was born the professional of the ergonomist whose purpose is to improve the performance of a system (production line, workstation, product design, etc) and the satisfaction of workers, protecting their welfare, health and safety.

It's a very important and indispensable role in field such as automotive, industrial and military.

#### **1.2.1** Virtual Ergonomics

Ergonomics approaches to workstation's assessment are beneficial to worker wellbeing by reducing the risk of exposing them to musculoskeletal diseases (MSDs). It is for this reason that for the protection of the workers have been introduced regulations that provide organizational measures in order to reduce biomechanical overload. The classical approach to meeting the standards involves analysis of static work postures. However, these approaches are very time consuming as they require analysis of all critical postures performed during a work action. That's why companies try to take advantage from the new technologies introduced with the advent of industry 4.0 by using them to optimizing the design process of new production lines.

Virtual reality is the most widely used technique in the latest ergonomic assessment approaches, this led to coin the term Virtual Ergonomics.

In a fully virtual environment, human-workstation interaction can be simulated using digital human models (humanoid) while the workstation can be imported using CAD models. Humanoids can be controlled and animated via direct or inverse kinematics [13].

## 1.3 Project's Purpose

The aim is to develop an application that is intended to support the ergonomist in the earliest stages of workstation validation by predicting how users, with different anthropometric percentiles, would behave in a work-station. The goal is achieved by using an inverse kinematic tool that, combined with postural rules defined by experienced ergonomists, is able to predict the movements of digital human model. The application is able to recognize any obstacles in the scene and appropriately reposition.

Based on the predicted postures, it is possible to verify the suitability of the workstation in relation to different anthropometric percentiles. The evaluation can be both qualitative, going to verify that the working points are reachable by all anthropometric percentiles but also quantitative going to perform a postural analysis by calculating joint angles. Indeed, the system allows to extrapolate a static pose and to submit it to the ergonomic screening system EAWS, a system widely used in FIAT infrastructure.

Being able to highlight any technical issues due to workstation organization even before having physical prototypes enables immediate action on workstation design while saving time and costs.

This project was accomplished thanks to CIM4.0 that provided the required technologies, such as an HTC-VIVE visor for virtual reality simulations and Xsens motion capture equipment; and thanks to Stellantis for supporting the industrial approach in workplace design and postural evaluation.

### 1.3.1 Competence Industry Manufacturing 4.0

The Competence Industry Manufacturing 4.0 (CIM 4.0) is a competence center that provides support for manufacturing companies that intend to improve their production processes aspiring to the digitalization of industrial processes based on industry 4.0.

# Chapter 2 Digital Human Model

This chapter is intended to summarize the state of art in the field of digital human modelling and their main use in the industrial manufacturing to simulate human interaction in the workplace.

A Digital Human Model (DHM) is a three-dimensional representation of a human that is placed in a simulation or virtual environment to visualize the effectiveness of a design before a physical prototype is constructed. The aim is to evaluate both safety and performance of the product [14].

A DHM to be representative of the human being should have all the functions of a real human such as anatomy, motion, dynamics, biomechanics, psychology, and physiology. However, it is not always necessary to have a good model of all these features. In fact, depending on the use-case, some features are more relevant than others and the model can be simplified.

According to (Zhu et al., 2019) we can distinguish two categories:

- Cognitive DHM, primarily used in journalism and social psychology to realize human-machine interaction based on emotions, languages, and facial expressions.
- Physical DHM that focuses on the body structures. These models are built for ergonomics research, with a focus on working postures and comfort. In this case, the model is a simplification of the skeleton and consists of bone segments, the number depends on the specificity required, that are connected by joints allowing a certain number of degrees of freedom.



Figure 2.1: Example of a Digital Human Model

## 2.1 Application of DHM

Digital human models are used in different fields like: automotive, industrial plants, aerospace, military and energy [15], but we can consider the automotive one as the main application field. The DHM has typically been developed for application in workplace and product design so in automotive field, they may be used for vehicle design processes [16] for example to analyze the inside of cars, concentrating on various features such as seat belts, steering wheels, control bottom position, etc. Another area of interest is the human-robot collaboration [17] [18] in order to assess the safety and efficiency of co-operation.



Figure 2.2: Example of how a DHM can be used for optimise human-robot collaboration

The evaluation is done through simulations where DHM are used to simulate the behavior of an operator interacting or performing a certain action in collaboration

with a virtual robot.

Another application example of particular interest is the staff education/training field, because typically safety instructions or processing steps are given through handbooks or videos. However, it's more intuitive see how a DHM interacts in a virtual environment, this approach increases learning interest and efficiency. Furthermore, the cost of education and training could decrease[19].

A final example, as well as the field of greatest interest, is the use of DHM for workplace design and optimization, which aim is to increase the productivity and reduce the risk of MSDs. Simulating the behavior of a user in a virtual environment using DHM brings out critical issues already in the early design phase of a workstation. This allows a rapid intervention to modify the project saving considerably in terms of time and costs.

These concepts just described can also be extended to the military or aerospace field but even in the healthcare even if, DHM has typically been developed for application in industry.

For example, they can be used to lessen the stress on medical professionals during laparoscopic procedures while also increasing the safety and efficiency of an integrated operating room [20]; to design specific custom-fit product such as a prosthesis socket [21]; to evaluate a bathing system design from caretakers and caregivers [22].

We can assume that industrial and medical fields are mostly comparable in respect to the aim of DHM. In fact, DHM are used, in both fields, for product design and optimization of the workplace. The main difference is about the necessity to customize the digital human modelling tools to suits health care requirements [23].

## 2.2 DHM software

Human modeling software enables designers to simulate human –workplace interaction by inserting a digital human model in the CAD generated work environment [24]. A few software commercially available for ergonomic evaluation are JACK, SAMMIE, RAMSIS, DELMIA, SANTOS, etc. These allow to choose the subject with which is wanted to characterize the action by changing the sex, age and percentile.

**RAMSIS** stand for "Rechnergestütztes Anthropometrisches Menschmodell zur Insassen-Simulation" and is an acronym in German for "Computer Aided Anthropological Mathematical System for Occupant Simulation", It's normally not used for the initial layout and complete design of vehicle's interiors. Most of the time, RAMSIS is only used to verify interior concepts [25]. It contains a manikin that well represents the human body, this manikin can be positioned and animated in a virtual space. The pose prediction system allows to constrain the DHM and calculate the most likely posture in the environment. It also allows to consider the possible presence of bulky clothing such as military uniforms and helmets. This system produces results that are reliable, objective, and reproducible [26].

The **Jack** human simulation system was developed at the Center for Human Modeling and Simulation at the University of Pennsylvania in 1980. At the beginning it was conceived as an ergonomic assessment and virtual human prototyping system for NASA space shuttle development but nowadays is sold as an ergonomic human simulation toolkit by Siemens [27] and is widely used for ergonomic evaluations of both product design [28] but also for the characterization of the interiors of vehicles such as cars, planes and trucks [9].

It includes a manikin with many degrees of freedom with the possibility to change its characteristics, it's also possible calculate internal joint torques.



Figure 2.3: Example of a simulation using Jack Siemens

Jack software includes a **3D static strength prediction program** (3DSSPP) module from the University of Michigan [29] and can stream real-time motion data [30].

The 3DSSPP is a human ergonomic modelling tool that predicts static strength requirements for tasks, it's an analyzer of slow movements since the biomechanical computations assume that the effects of acceleration and momentum are negligible. Such tasks can be better evaluated if the activity is break down into a sequence of static postures and then analyze each individual posture. This system provides first approximation of the movement thanks to automatic posture generation feature that includes posture data, force parameters and anthropometry. The algorithm is based on the hand positions and orientations (externally insert by the user), torques and forces on the hands and joints. However, the inverse kinematics algorithm may not yield a posture representative of the actual posture being modelled since the actual posture can be affected by individual factors. To minimize these effects, only experienced workers should be observed performing the tasks in question. The developers recommend that it should not be used alone when predicting static strength and job design requirements. The authors (Mgbemena et al., 2020) also confirm the necessity of the presence of an experienced ergonomist and a training phase before using this system. This tool has many features for example it's possible to work in forward kinematics by positioning the mannequin in the pose you want to evaluate, can simulate barriers / tables or add objects that will be symmetrically held by the manikin.

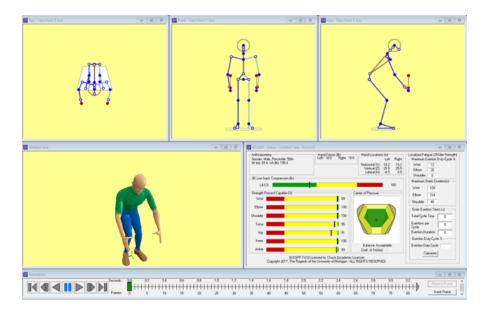


Figure 2.4: Editor layout and example of a predicted pose by 3DSSPP

Similar approaches to 3DSSPP are the ErgoToolKit [31] and the ViveLab Ergo developed in Hungary [32]. The first one can quickly identify postures due to Posture Definition (manual or semi-automatic) and Recognition tools. To manually pose the manikin the user has to set the minimum and maximum value for each joint and every side of each segment. When the system works in semi-automatic mode, the pose (standing, sitting, stepping, etc...) is recognized by performing IF-THEN-ELSE checks on the positions of the kinematic chains. More than one check is done on a single chain. Instead, to perform posture recognition during the simulation, it's needed the lengths of the segments, the position vectors composed by the rotation angle values of the manikin's joints and the spatial data composed by the position of the digital mannequin body segments. Posture Definition and Recognition method identify unfavourable postures with the goal of improving workplace design. This result can be further elaborated using the Stress Screening Tool based on the Automotive Assembly Worksheet (AAWS) method. These initial tests can be easily made by people who have basic ergonomic knowledge so ergonomic experts can focus on more complicated ergonomic assessment tasks. The ViveLab Ergo is an online ergonomic system for virtual testing and verification

Posture Definition & Recognition 📃 🗌 [	😸 Posture Definition & Recognition 📃 🗌 📔	📕 Posture Definition & Recognition 📗
He	He	
Manage Postures Manual Posture	Manage Postures Predefined Posture	Manage Postures
Details for posture: 'walk'34'. Select SegmentDOF Tento Foot Tunk ODF Def: DDF1 V Japons Segment	Details for posture: "StandUpAH". Lower body Squating Stiting Standing Stiting Knee Stepping Incline Plane Arms position	Invalid Postures
Min: -11.25 Max: 8.75 Tolerance (deg) Update © DOF	Below Shoulder Above Shoulder  Above Head  Upper bady  Upright Bend Forward	O Invelid O Valid Manikins Manikin1 Add Remove
Segment	Deeply Bend Forward	Clear
All Apply Tolerance in both sides	Whole body Lying	Recognize View Posture

**Figure 2.5:** Example of ErgoToolKit setup for Posture Definition and Recognition tool by using manual posture definition or semi-automatic posture definition

of product or manufacturing processes, this is possible because simulate interactions between the human and the machine. The first step is to select the type of

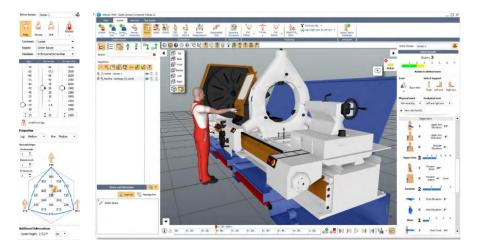


Figure 2.6: Example of editor layout in VeviLab Ergo

mannequin by specifying sex, percentile, weight, age and even nationality. Then, the mannequin can be posed by choosing the pre-set body postures available in the appropriate menu. There is the chance to customize poses. This static pose is then used to simulate user-machine interaction. There is no real interaction with the machine as this is just a CAD model imported into the scene. It is only possible to evaluate the ergonomics of the static user pose.

It is possible to create animations, in which the manikin performs specific actions. The animation can be created using records (supports records made by Xsens MVM motion capture technology [33]) or by defining a certain number of poses over time

as shown in Figure 2.8.

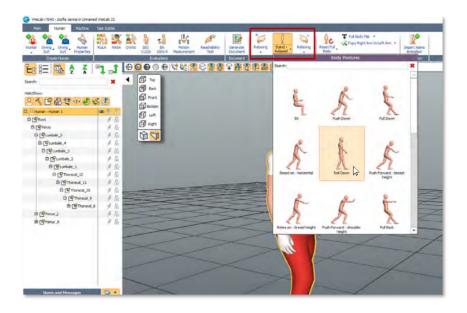


Figure 2.7: Pre-set body postures available in ViveLab Ergo

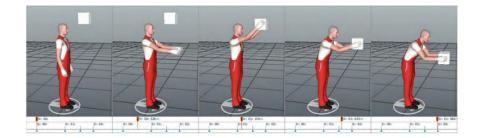


Figure 2.8: Example of how create an animation using ViveLab Ergo

In ViveLab Ergo system several types of analyses are implemented for evaluating human motion and posture like: RULA, OWAS, NASA-OBI, ISO 11226, EN 1005-4, Motion Measurement and Reachability Test. This tool allows to evaluate the user's reachability with reference to the hand of the mannequin. This area is updated every time the characteristics of the manikin are modified such as percentile, sex or age. The Motion Measurement function may be used to view or estimate the distance traveled by a human character during animation.

However, these programs are quite sophisticated and need extensive training as well as a significant amount of processing [34]. For example, the positioning of the DHM as in the case of ViveLab Ergo may be very complicated especially if you do not have experience in the field. Even the most widespread and innovative systems such as Jack and RAMSIS, due to their innovation are very sophisticated and require a training phase and the support of experts.

Alternatively, the Fiat Group Automobiles (FGA) proposes the Human Model, a simple and easy instrument developed by Fiat Chrysler Automobiles (FCA) in cooperation with the academia. It can be used by ergonomists that are inexperienced at virtual modeling after only a brief training period because developed in the Microsoft Excel environment with the assistance of the Visual Basic programming language. It's very useful for early checks in the design phase because provides real-time results. The Human Model is a simulation tool that allows to ergonomically evaluate a workstation [35].

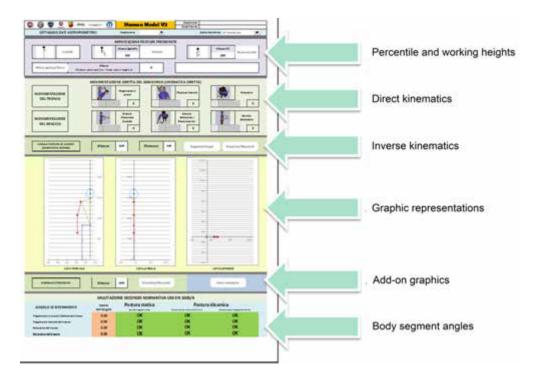


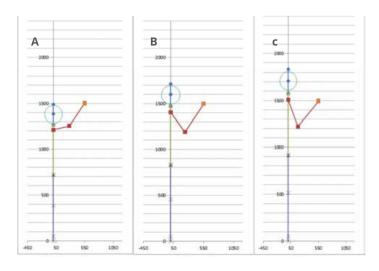
Figure 2.9: Layout Human Model System

Given the working points of the hands, it predicts the most probable pose that a worker may assume. The added value of this system is the possibility to compare the predicted pose of mannequin with different anthropometric percentiles and thus validate a workstation taking into account the needs of the 5th percentile but also of the 95th.

The system is designed to work in a plane so, when the chosen mode is inverse kinematics, it is necessary to provide, as input parameters, the quote (Z coordinate) and distance (Y coordinate) of the target, X coordinate is automatically aligned to the elbow. The DHM model used in this system is a simply 2-D multibody model [36] is characterized by a set of rigid segments with zero mass and connected by joints. Each segment has its own specific length.

The direct kinematics mode on the other hand allows the positioning of the mannequin by choosing from a number of poses such as crouching, standing, sitting or walking.

An example of how the predicted pose varies as the percentile varies is reported in figure 2.10. If the great advantage of the Human Model is its simplicity, one of its limits is surely the impossibility to work in a 3D environment and thus to achieve realistic postures.



**Figure 2.10:** Predicted poses by Human Model system: 5th female percentile (A); 50th male percentile (B); 95th male percentile (C)

All ergonomic assessment systems that are based on the use of digital human models should have the following tools to be useful:

- 1. Anthropometric database to consider the variability in human body size among different populations in order to ensure that the product or workstation can meet the safety and comfort requirements for most percentiles;
- 2. Direct or inverse kinematics to take into account the human-machine interaction;

3. Ergonomic risk assessment with the implementation of ergonomic metrics in order to reduce musculoskeletal diseases.

### 2.3 Anthropometric database

The term percentile refers to the subdivision of the population into groups characterized by precise anthropometric measures.

By definition, the anthropometry is the measurement of height, weight and segments lengths such as head, trunk and limbs. These dimensions are measured between anatomical or architectural points of reference [37].

Anthropometric data can be accessed from ISO 7250-1 and ISO/DTR 7250-2 [38] [39], the first one provides an explanation of anthropometric measures that may be used to compare demographic groups. Instead, the second normative provides access to the database of all measurements, being able to distinguish between populations of different nationalities. In the specific case of this project, reference was made to the Italian population and to the 5, 50 and 95 percentiles for both men and women.

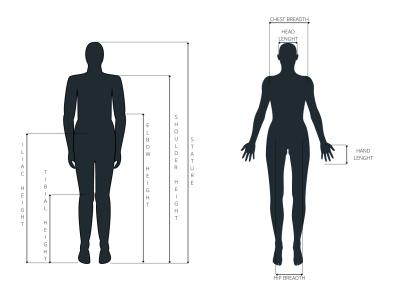


Figure 2.11: Basic anthropometric measurements

Given a certain anthropometric measurement, a percentile is defined as the percentage of a population that is above or below that measurement for example, if the

Body Measurement		
Stature	Vertical distance from the floor to the highest point of the head	
Shoulder height	Vertical distance from the floor to the acromion.	
Elbow height	Vertical distance from the floor to the lowest bony point of the bent elbow	
Iliac spine height	Vertical distance from the floor to the anterosuperior iliac spine	
Tibial height	Vertical distance from the floor to the tibiale	
Chest breadth	Breadth of the torso measured at mesosternal level	
Hip breadth	Maximum horizontal distance across the hips	
Hand length	Perpendicular distance from a line drawn between the styloid processes to the tip of the middle finger	
Head length	Distance along a straight line between the glabella and the rearmost point of the skull.	

 Table 2.1: Description of anthropometric measurements

stature of the 90th percentile male is 1.85m means that 10% of the male population is taller while the other 90% is shorter.

The distribution of percentiles is a Gaussian so the scale is not linear and usually has a peak near the 50th percentile. This means that the 50th percentile is, in these cases, the one that represents the majority of the population.

These documents are designed to be a reference for ergonomists whose job is to evaluate the safety of the user-product interaction that's because anthropometry is an excellent indicator of how people physically interact with items. During the design phase, it is important to consider the variability in human body size among different populations. It is the ergonomist's job to ensure that the product or workstation can meet the safety and comfort requirements for most percentiles [40] [41]. Depending on the product parameters, the ergonomist decides which percentiles to focus on throughout the assessment. In the automotive fields it's common to work with 5th, 50th, and 95th for both male and female that's because the aim is to extend the usability of the product to the majority of people.

### 2.4 DHMs for ergonomic risk assessment

All the systems described in paragraph 2.2 contain a tool able to analyze the pose of the mannequin and evaluate its ergonomics. Evaluating in advance the risk associated with each pose that the worker could assume is very important, first for the well-being of the worker but also to boost productivity. The main metrics used have the common purpose of reducing musculoskeletal diseases by assessing worker's exposure to risk variables that might cause trauma in the body, such as postures, repetitiveness of motions, applied force, and static musculoskeletal activity. The lower back, neck, shoulders, elbows, forearms, wrists, and hands are the most commonly afflicted body parts during manual work in an industrial environment [42].

The most widely used metrics:

- 1. **RULA** stands for "Rapid Upper Limb Assessment", this metric was designed to rapidly assess ergonomic risk factors related to the posture of the upper limbs, neck and trunk also considering the muscle functions and load on the body. The tool generates a single score of the investigated task indicating the amount of intervention required to decrease the risk of worker discomfort [43].
- 2. **REBA** stands for "Rapid Entire body assessment", this metric evaluates both upper and lower parts such as the trunk, legs, neck, shoulders, arms, and wrists, load handled, coupling type, etc. Like RULA, the result is only one score that considers all body parts. The score corresponds to the associated risk level. A lower value of REBA score means that there is no urgency of intervention, otherwise urgent action is needed [44] [45].
- 3. NIOSH Lifting Equation is a mathematical equation that give a method for quantifying the risk of low back diseases caused by frequent lifting tasks. The equation (2.1) is published by the National Institute for Occupational Safety and Health (NIOSH).

$$RWL = LC * HM * VM * DM * AM * FM * CM$$
(2.1)

To be solved it is necessary to have as input parameters the position of the object in the space, the frequency with which the action is performed and the twist of body. The lifting index (LI) is the ratio between the load weight and the RWL. This index provides an assessment of the MSD risk and physical stress associated with the manual lifting actions.

A value of LI  $\leq 1$  is associated to a low risk while a value between 1 and 3 to a medium risk. When the index LI is higher than 3 the associated risk is high [43] [46].

- 4. **OCRA** is a recent method of assessing the risk from biomechanical overload caused by the performance of repetitive movements of the upper limbs.
- 5. EAWS stands for "Ergonomic Assessment Work-Sheet" and evaluate the risks associated with static and dynamic postural load, force applications, load carrying, and repeated limb movements which an operator is exposed. The score depends on the intensity of the loads of the actions and their duration [47].

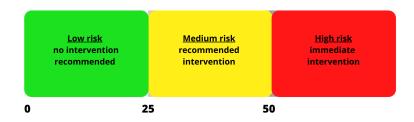


Figure 2.12: EAWS: A score between (0-25) means that there is no risks or that the risk is low so no action is needed; if the score in between (25-50) there is a medium risk and a redesign is recommended; if the score is higher that 50 the risk is high and the workstation must be redesign.

The EAWS protocol is the most widely used in the automotive industry [48]in fact, it is the main method used by stellantis for workstation evaluation [49].

6. **MTM** stands for Methods-Time Measurement [50], this method allows to analyze an action going to subdivide it in a certain number of micro-actions, each of them is characterized by the same time-step.

The main feature of this method is the possibility of being able to evaluate a workstation even before implementing it, simply by relying on the experience of an ergonomist who knows the activity that will then be performed.

## 2.5 Prospective: DHM in virtual reality

Currently, the most widely used approach to evaluate workstations, in the early stages of design, is to use DHM-based desktop simulation software such as those mentioned in section 2.2. These systems are practical when the aim is to evaluate simple workstations or when it's needed to modify an existing one. However, when the analysis requires greater complexity, these systems are no longer suitable as they would involve more "work" by the operator [51] especially in the positioning of the mannequin. This phase is very important because it determines the further evaluations and may be influenced by the operator's experience that is using the system.

To overcome these limitations, more innovative approaches are moving towards new Industry 4.0 technologies in particular Virtual Reality. VR allows for the creation of realistic and interactive virtual environments that immerse the user and try to mimic its actions/reactions. The added value of this technology is actually the possibility of being able to take into consideration new scenarios for assessing cognitive characteristics and to improve operational performance quality.

The introduction of Motion Capture Technologies and Virtual Reality, in manufacturing field, according to [6], can help with ergonomic workplace assessments. In fact, the combination of these two technologies enables ergonomic assessments to be performed fast and correctly.

There are already many studies that are opting for this new approach like [51] that proposes a Mixed Reality system for the ergonomic assessment of industrial workstations. They proposed a system that integrates motion capture tools, a head-mounted display device relate to Unity3D platform (described in section 3.4), and ergonomic analysis software such as Jack. This system improves the realism of the simulation and the reliability of the results because the operator is immersed in a virtual scenario and can interact with physical components. The physical interaction instead of simulating a human-machine interaction is more efficient allowing to significantly reduce time and costs.

There are also approaches with augmented reality, the authors (Belo et al. 2021) provide a method for calculating the interaction cost at any point in the user's surroundings that may be reached. As a result, throughout the design process, all ergonomic data are available, allowing ergonomists to immediately discover the postures that maximize user comfort. In fact, many companies are already using these new technologies to improve their production steps. Stellantis, in collaboration with CIM 4.0, proposes an application framework. This framework is able to process, through the use of inertial motion capture technologies, the poses assumed by the subject during the user-workplace interaction. It's possible to perform a postural analysis by assessing joint's angles, these information are also processed in order to obtain the EAWS score for the evaluation of the posture.

# Chapter 3

# Methods and software technologies

This chapter will describe in detail the technologies used to achieve the intended result, in particular as a development environment it was decided to use the Unity3D platform, certainly, the most widely used for creating virtual reality applications. Working in Unity environment has allowed to exploit the Xsens plugins such as Xsens MVN Animate in order to have a character able to be animated in real-time in the 3D environment developed. The use of Xsens motion capture system and its plugin in Unity, has allowed to obtain the application points of hands and feet that will be provided as input parameters to an inverse kinematics algorithm. The inverse kinematics algorithm, supported by the postural rules, will then be able to predict the potential pose that a user could assume in the workstation developed in the 3D environment.

# 3.1 Virtual Reality's technologies

The word Virtual Reality refers to a group of technologies capable of producing a new and virtual environment that replaces the real world temporarily and entirely. When it comes to virtual reality, according to (Sherman and Craig 2002), there are three crucial qualities to consider:

- 1. Immersion: the virtual environment is perceived as real. To establish an alienation from the actual world and to maximize the impression of immersion, it is crucial to activate as many sensory pathways as possible;
- 2. Presence: the sensation of being a part of the virtual world;
- 3. Interactivity: user interfaces with the virtual environment.

The user's high immersion capacity in the virtual world is provided by the replication of high-definition and 360-degree environments, as well as the usage of sophisticated devices such as headsets and intuitive and responsive manual controls. There are currently several technologies in the market that can be used to implement a virtual environment. The CAVE systems (Cave automatic virtual environment) are traditional VR setups that use from three to six projected display that entirely surround the viewer. Users must wear 3D glasses and interact with it using a controller to see the 3D images. It is considered an immersive technology as users can get a 360-degree view, however, is less invasive and has fewer side effects than the use of a visor, the latter considered as the most innovative technology on the market.

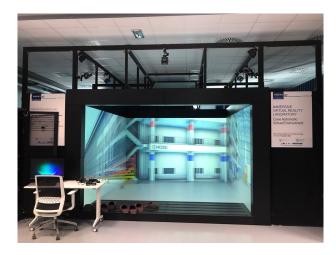


Figure 3.1: Cave automatic virtual environment



Figure 3.2: HTC Vive Headset

The most widespread visors are HTC VIVE [54] and Oculus [55], users can see 3D stereoscopic pictures and establish their spatial position in the visual world by wearing an HMD helmet with motion tracking sensors. In the meanwhile, users may listen to sounds through headphones and interact with virtual items using joysticks. These systems are certainly more convenient as they are more versatile, easily transportable and do not require assembly. However, they have more side effects such as headaches, nausea and eye strain.

Virtual reality owes its origins to the world of gaming but, in recent decades, its use is expanding to numerous other fields of application. The usage of virtual reality in industrial design, for example, may be used for workstation optimization, virtual simulations, prototyping, and staff training. This technology allow to preserve both quality and efficiency of manufacturing, but also the well-being and health of employees.

Also revolutionary is its use in health-care. Implementing a surgeons training phase in a virtual environment both in the pre-operative stages and during the academic period allows medical staff to gain more awareness lowering patient risk [56]. Beyond its uses in surgery, VR may be used to replicate activities and exercises intended to assist patients in their physical recovery.

# **3.2** Inverse Kinematics

Kinematics is the study of the rotational and translational motion of points, bodies, and systems. This approach doesn't concern what is the cause of the motion. We can distinguish between forward and inverse kinematics, Forward kinematics identifies the position and orientation of the end-effector for a given configuration of its joints, whereas Inverse kinematics predicts the configuration of humanoid's joints in order to make the end-effector achieve the desired position and orientation [57].

The idea of inverse kinematics originated in the field of robotics in particular to solve the problem of positioning a robotic arm in a specific and pre-defined position. Beyond its use in robotics, IK has found applications in computer graphics, generating particular interest in the field of animating articulated subjects.

In order to move a character, a rigid multibody system needs to be defined. It consists of a set of rigid objects, called links, connected together by joints. A joint is the component concerned with motion, it permits some degree of relative motion between the connected segments. Each segment has its own length, shape, volume and mass properties. The kinematic chain is an arrangement of rigid components connected by joints that provides constrained movements. Once the rigid multibody system is defined it can be animated using forward or inverse kinematics. If FK is used, the problem has a unique solution depending on the transformation applied to the chain. Otherwise, if IK is used, the problem has more than one solution that not always can be achieved. Can happen that the goal is unreachable or that two or more tasks conflict and cannot be satisfied simultaneously. Unreachable targets are the targets which can be further than the point that the chain can reach. These problems are defined as over-constrained.

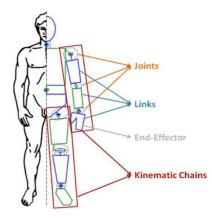


Figure 3.3: Multibody system is composed by a set of rigid objects, called links, connected together by joints; source: www.rosroboticslearning.com/forward-kinematics

An aspect that should not be underestimated when talking about IK solvers is that often there is more than one possible solution to the problem.

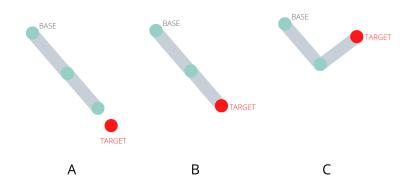


Figure 3.4: Possible solution of IK solver: situation A the target cannot be reached, solution B there is only a solution, solution C more than one solution is possible.

#### 3.2.1 IK solver

The resolution methods are divided into non-heuristics methods, such as Jacobian, Newton and the Sequential Monte Carlo, and into heuristics methods such as FABRIK and CCD, which are generally faster. The first type of method developed to solve the IK problems is the one based on the definition of the **Jacobian matrix** that contains all the partial derivatives of the chain systems with respect to the end-effectors. Each term represents how a change of the joint angle effects the spatial location of end effector. The Jacobian matrix is defined as reported in equation (3.1)

$$J(\theta)_{ij} = \left(\frac{\partial S_i}{\partial \theta_i}\right)_{ij} \tag{3.1}$$

There are several variants depending on how the problem is approached, for example it's possible to calculate the transpose or the inverse of the Jacobian matrix, in any case the solution of the problem is a linear approximation of the end effector's movement. This family of methods is useful when approaching systems with many kinematic chains, however, it's important to keep in mind that they can lead to unrealistic solutions of the problem. In addition, they are not very fast and can suffer of singularity problems.

Another example of non-heuristic solver is the **Newton Method**, a minimisation problem which consist in the calculation of the Hessian matrix that is not easy to implement and it requires a high computational cost. The approach just described require complex numerical operations and may suffer of singularities [58].

A valid alternative could be using a sampling approach like **Sequential Monte Carlo Methods**. As a result of an optimization technique, the algorithm generates a full motion from the initial location to the goal position, satisfying all the constraints [58].

Instead, heuristic methods have different approaches and are the most used IK solver for animate articulated bodies. Cyclic Coordinate Descent (CCD) is an iterative search technique that performs a transformation to a joint that brings the end-effector as close as possible to the target and then does the same with the next joint. This is done until a satisfactory solution is obtained. It's a very simple and rapid technique to implement if there are only few end-effectors and each interaction has a low computational cost [58]. However, is a local method so has problems with the convergence.

The most widely used method to solve inverse kinematics problems is the **FABRIK** which stands for Forward And Backward Reaching Inverse Kinematics. It converges very quickly and allows to obtain, in the case of animation of human models, very physiological and realistic poses. It is a very versatile technique that allows you to work with one or more targets and to incorporate constraints in order to work with complex multibody systems. A well-constrained model can limit the number of possible postures, resulting in a more realistic motion. The principle underlying the method is to apply first a forward kinematics from the start joint to the end-effectors and then apply an inverse kinematics from the end effector to the first joint. The procedure is then repeated, for as many iterations as needed,

until the end effector is identical or close enough to the desired target [59]. Table 3.1 summarizes and compares all the main features of the various methods used for solve IK problems.

FABRIK	CCD	JACOBIAN	NEWTON
No problem of singularities	No problem of singularities	Suffer of singularities due to the inversione of the matrix	No problem of singularities
Rapid convergence	Rapid convergece	Slow convergence	Converge faster than FABRIK but slower than CCD
Easy to add constraints	Easy to add constraints	/	Complex and difficult to implement
Natural movements in real-time	Real time solver but generate unrealistic posture. Work better when the target is close to the end-effector	Unrealistic movements and with oscillation and discontinuities	/
Extended to a multiple end-effector	Problem with multiple end-effector	Can be extended very easily to multi end-effector problems	/
Low computational cost	/	/	High computational cost

Table 3.1: Tab1 chapter3

According to (Aristidou et al. 2018) we may deduce that the fundamental issue with heuristic approaches is that they provide unrealistic postures as results. It is not enough to simply establish constraints in these situations. The issue is that each joint is considered separately from the others, thus we don't take into consideration global constraints but only individual ones.

When the purpose is to animate a multibody system, such as a hand or a human body, it is important that the chosen resolution method can satisfy these requirements:

- 1. Set constraints on the model in order to obtain realistic results. Imposing constraints implies to define ranges in which the joint can rotate. In this way, the solution to the IK problem means that the kinematic chain can only assume realistic poses;
- 2. The algorithm should be able to deal with multiple end-effectors.

# 3.3 Motion Capture Technologies

The set of processes used for digitally recreate the movement of people and/or things is referred to as motion capture, often known as mo-cap or mocap [61]. Motion capture systems are divided into optical and non-optical systems. The optical ones require the use of markers that can be active if the recognition occurs by LED lighting of the marker itself or they are passive when the lighting of the markers occurs through IR cameras. These systems are the most precise and allow for detection over a large area, but they are also the most expensive and difficult in terms of calibration. Additionally, there is the issue of occlusion of the marker by the camera, which leads to mistakes in movement reconstruction.

Another family of mocap technologies makes use of non-optimal systems among which we distinguish:

- 1. Electro-magnetic: utilize emitter-receiver systems, in which the emitter is made up of three windings, each of which produces an electromagnetic field. In terms of location and orientation, the sensor can rebuild the absolute position. They are only functional when the distance between the sensor and the emitter is kept to a minimum.
- 2. Electro-mechanical: measure the bend of various joints of the user. Are the least used systems because they are cumbersome and difficult for operators to fit.
- 3. Inertial tracking: It is a set of three sensors: an accelerometer, a gyroscope and an magnetometer. It is a system that reconstructs relative movement using the dimensions of the user's bone segments as input information. It has lower resolution than optical systems, but it is cheap, enables for large-area operations and is easy adaptable [33].

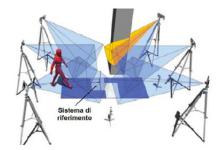


Figure 3.5: Optical system set-up for motion capture



Figure 3.6: Electro-magnetic system for motion capture



Figure 3.7: Electro-mechanical system for motion capture



Figure 3.8: XSens an example of inertial system for motion capture

#### 3.3.1 Application fields

Motion capture technologies are very versatile and therefore can be used in the most disparate fields. However, the main application fields can be identified as entertainment (such as films and video games), health and sport [62].

Motion capture makes it possible to recreate and later analyse human movement, which in sports means that it is possible to assess the physical condition of athletes, their technical performance, and the mechanisms of injury and prevention [63].

In gaming it is useful for recreating animations and being able to easily animate characters.

In the health field, bio-engineering applications are very interesting, such as gait analysis [64] to evaluate the presence of possible pathology during the walking, or to evaluate the patient's status during his rehabilitation process [65] [66]. In these circumstances very high resolution is requested by mo-cap technology, which is why optical systems are commonly adopted [67]. Otherwise, when a high level of accuracy is not required the most used technology is the inertial one. For example, it is used in industry to perform ergonomic analyses [68]. The strategy described by (Caputo et al., 2018) aims to make the design of the workstation but also the design of new products more human-centered. A key role in this new approach is precisely the use of motion capture technologies.



Figure 3.9: Example of how mocap technologies can be used in manufacturing field: the user wears Xsens technology for motion capture while is performing work actions. The movement is digitally reconstructs and then an ergonomic assessment is performed using JackSiemens. Source: [69]

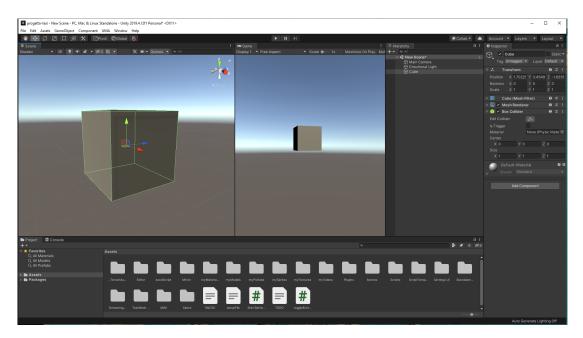
# 3.4 Unity3D

Unity [70] is a platform developed by Unity Technologies that allows the implementation in a 3D environment of real-time animations or interactive applications such as video games and virtual and augmented reality applications. It has the great advantage of being very easy to use even for those who don't have a programming background, since it lets you do a certain number of actions through editing. For more complex projects, for example if you want to define a specific behavior for objects it's possible to define scripts in C Sharp (also known as C#) by the support of Visual Studio, in fact C# is an object-oriented programming language developed by Microsoft.

The Unity editor consists of different panels, each of which performs specific functions:

• Hierarchy: includes a list of all the objects in the scene. A parent-child relationship can be defined between these objects. All modifications made to the father, such as translations, rotations and scaling, will also involve the son;

- Scene: displays a view of the scene you're working on, as well as the items it includes (lights, cameras, 3D models, etc.). It allows you to operate directly on objects to translate, rotate, and scale them. Multiple scenes can be included in a Unity application;
- Game: simulates the execution of the application, any object captured by the camera is shown in this window;
- Inspector: presents all the properties and components of an object selected in the scene;
- Project: displays the assets present in the project, such as libraries, scripts and animations;



• Console: displays compilation-related messages such as errors and warnings.

Figure 3.10: Unity editor

#### 3.4.1 Visual Studio

Visual Studio [71] is a development environment owned by Microsoft Windows in which extensions and add-ons can be created and used. The environment includes a code editor that supports several programming languages including Java, JavaScript and C#.

#### 3.4.2 GameObject

Unity is characterized by a scene where the main element is the GameObject. A GameObject can represent a character or an object in the environment. Unity allows to create only simple objects such as spheres, cubes etc but also offers the possibility to import more complex models made on specialized modeling platforms. Each GameObject has a component called Transform that contains details about the object's position and orientation. The position information is contained in a three-dimensional vector with X,Y and Z coordinates. The rotation information is instead stored as a quaternion, a four-dimensional vector with X,Y,Z and W coordinates. When the rotation of an item in a scene is zero, the global and local reference systems are aligned. Instead, when a rotation is applied, as in the case of figure 3.11 where there is a rotation along Y of 30° then there is no more corrispondence between the two systems.

Both types of information may be accessed both with respect to the global system of the scene and with respect to the local reference system of the object.

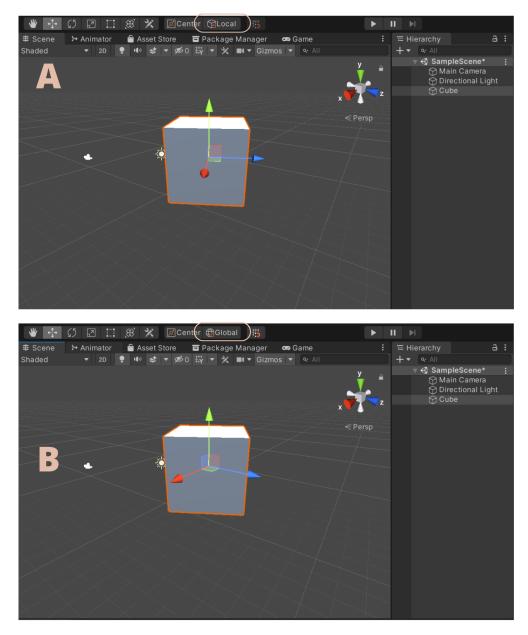
It is possible to associate to the GameObjects some additional components that are included by default in Unity or that may be downloaded from the Asset Store. The main components are:

• Collider: manages the collision between objects in the scene. Different shapes can be used, such as box or sphere, for complex objects you can use the MeshCollider component. Once a Collider component is applied to a GameObject, it starts detecting collisions with other Colliders. The OnCollisionEnter(Collision obj) function is called in the frame where the collision occurs, and the OnCollisionExit(Collision obj) function is invoked in the frame where the collision occurs. The OnCollisionStay(Collision obj) function is active for the duration of the collision. When a collision happens, these routines can be used to define a certain type of behavior.

For the activation of these functions it is important that the GameObjects have associated the RigidBody component;

- RigidBody: this component allows to move GameObjects and make them interact according to the laws of physics. It is possible to add the gravity associating also a weight force to the object improving the simulation of fall of the object but also of interaction with the other GameObject; have a friction in collisions with other objects, and a resistance to movement (drag) that can be used for many purposes, including to simulate the speed limit that objects have in real situations of friction with the air. Another very useful function is the possibility of adding forces definable in modulus and direction
- Material: this component allows to customize GameObjects. The material can be a color modification or a component downloaded from the Unity store

to simulate the effect of wood, marble, ceramic, steel etc.



**Figure 3.11:** Unity reference system: local reference system (A), global reference system (B)

All the information associated to a GameObject can be accessed through scripts and used in real time, they can also be modified e.g. by turning gravity on and off, moving/or rotating the object.

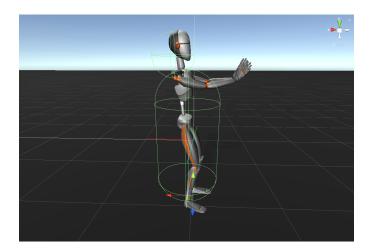


Figure 3.12: Example of collider attached to a *GameObject* 

## 3.5 Root Motion

Within the Unity Platform, there is a store where supporting plugins can be downloaded for free or for a paid. To develop the proposed work, it was decided to use the Final IK [72] [73] an inverse kinematics plugins whose main application is in the production of videogames and a license for educational purposes was obtained. A variety of high-speed IK components are included in Final IK, the ones used for this project were FullBodyBiped Ik (FBBIK) and LookAt Ik.

FBBIK is a useful component for animating biped characters such as DHM to whom an avatar is associated. In Unity the term avatar refers to an animated model that has a humanoid layout and indicates which components of the model belong to the legs, arms, head, and body.

It is necessary a first initialization step, which can be done in manual or automatic mode, using in the latter case, the auto-detection function. After verifying that the DHM is associated with an avatar that successfully matches the humanoid's bone segments, the auto-detection initialization works appropriately. In the following project the use of the FBBIK tool and the references auto-detection function has allowed to bypass the animation rigging section which is required in Unity in order to animate characters. The next step is the definition of the kinematic chains, our body has a total of five kinematic chains: body, arm and leg both right and left. The root chain is the body, consisting of a single node, and the limbs are its children. A node is a member of the chain. For instance, an arm chain contains three nodes: upper arm, forearm and the hand. When arm or leg chain is considered, it may be useful to define the bend constraints in order to control joint angles. An example of kinematics chain definition is shown in Figure 3.14.

The auto-detection function automatically defines effectors such as spines, hands,

🔻 쳙 🗹 Full Body Biped IK		07‡ :
Fix Transforms		
References		
	A MvnPuppet (1) (Transform)	
Pelvis	Hips (Transform)	
Left Thigh	LeftHip (Transform)	
	LeftKnee (Transform)	
Left Foot	LeftAnkle (Transform)	
Right Thigh	L RightHip (Transform)	
Right Calf	RightKnee (Transform)	
Right Foot	🙏 RightAnkle (Transform)	
Left Upper Arm	LeftShoulder 1 (Transform)	
Left Forearm	LeftElbow (Transform)	
Left Hand	LeftCarpus 1 (Transform)	
Right Upper Arm	RightShoulder 1 (Transform)	
Right Forearm	A RightElbow (Transform)	
Right Hand	RightCarpus 1 (Transform)	
	🙏 Head 1 (Transform)	
▼ Spine		
	🙏 Chest (Transform)	0
Element 1	L Chest2 (Transform)	0
▶ Eyes		

Figure 3.13: FullBodyBiped IK references

feet, hips, and knees (right/left), as well as a target transform for each of them. FullBodyBiped IK has three types of effectors:

- 1. end-effectors such as hands and feet;
- 2. mid-body effectors such as shoulders and thighs;
- 3. multi-effectors like the body.

The rotation of end-effectors can be changed, but the rotation of the mid-body and multi-effectors has no effect. The bending direction of the limb is also changed as the end-effector rotates (unless you are using bend goals to override it). The body effector is a multi-effector, which means it drags both thigh effectors along with it, this allows to simplify the positioning of the body. The parameter *positionOffset* attribute on effectors may also be used to simply manipulate the underlaying animation. After each solver update, effectors' *positionOffset* will be reset to *Vector3.zero*.

A target is defined as the element that the effector is intended to reach. Each target has a rotation and position weight associated; while the weights are zero, the effector will not try to attain the same position as the target instead, when the weights are one, the effector will position itself as the target element. The system allows to have active more effectors at the same time.

Once the character has been initialized, in order to obtain natural movements, it is important to verify that the rotations are correctly applied to all the limbs meaning that the bend directions are correctly identified.

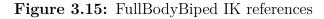


Figure 3.14: FullBodyBiped IK references

If they are identified incorrectly, it is possible to proceed in two ways:

- 1. Slightly rotate the segment along the correct bend direction;
- 2. Modify by scrip the axes on which the rotations are applied using the function *SetLimbOrientations*.

Bend Constraint				
Bone 1	None (Tran	sform)		
Bone 2	None (Tran	sform)		
Bone 3	None (Tran	sform)		
Bend Goal	None (Tran	sform)		
Direction	X 1	Y O	ΖO	
x				
Y				
Z				
w				
Weight	•			
Default Local Direction	хо	ΥO	ΖO	
Default Child Direction	хо	Y O	ΖO	
► Element 1				
► Element 2				
► Element 3				
▶ Element 4				



🔻 💏 🗹 Full Body Biped IK				0	74 i
Fix Transforms	~				
▶ References					
▼ Solver					
IK Position Weight			•	1	
		•			
▶ Chain					
	9				
► Element 0					
► Element 1					
► Element 2					
Element 3					
► Element 4					
	🙏 LeftCarpus 1 (Ti	ransform)			
Target	None (Transform)				
Position Weight	•				
Rotation Weight	•				
	X 0	Y 0	Ζ 0		
▶ Rotation					
Position Offset	X 0	Y 0	Ζ0		
Effect Child Nodes	~				
Maintain Relative Position Weigh	•				
Child Bones					
Plane Bone 1	LeftShoulder 1 (	Transform)			
Plane Bone 2	&RightShoulder 1	(Transform)			
Plane Bone 3	LChest2 (Transfo	rm)			
Plane Rotation Offset					
Element 6					
► Element 7					
► Element 8					

Figure 3.16: FullBodyBiped IK references

After verified the correct functioning, FBBIK can be customized to meet specific requirements of the project.

1. Pull property is a characteristic of each chain. When all chains have pull equal to 1, pull weight is distributed equally between the limbs. That means reaching all effectors is not quaranteed if they are very far from each other that's because the pull weight determines how much this limb is able to pull other limbs. Otherwise, when the left arm chain has pull weight equal to 1 and all others have 0, it's possible to pull the character from it's left hand to Infinity without losing contact;

- 2. Reach parameter can be used to pull the body closer to the end-effector;
- 3. Push parameter can repels an effector when it comes too close;
- 4. Spine stiffness makes the spine stiffer

Another component used in this project is LookAt IK that can rotate a set of bones to face a target, in particular this component was used to rotate the head. The initialization provides the definition of the spine bones, in this specific case three segments have been identified and the definition of the target, that is the object towards which the mannequin torso must orient itself. An example of how LookAt Ik works is provided in figure 3.18.

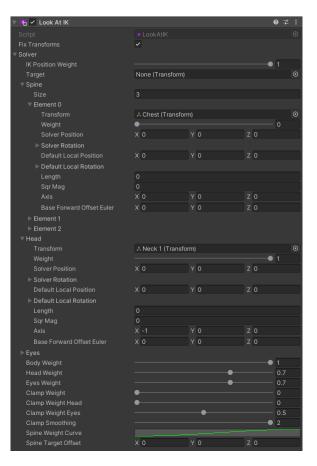


Figure 3.17: LookAt Ik Inspector

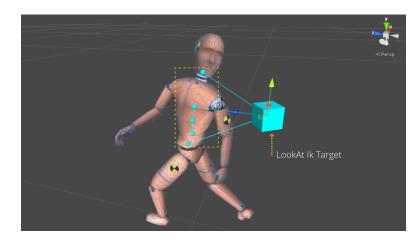


Figure 3.18: LookAt Ik Example

The components that characterize the FullBodyBiped Ik and LookAt Ik are all modulable meaning that each element and parameter defined previously may be changed using either the editor or by script. This enables the real-time tool to be adapted to the particular requirements of the project, resulting in a system that is always functioning and adequate for any circumstance. This implies the possibility to enable/disable the weight of any type of effector, change its target, define a bend constraint and also change the values of the parameters without the intervention of a user via editor.

# Chapter 4 Design and Development

The developed application is intended to support the ergonomist in the earliest stages of workstation validation. The goal is to predict how users with different anthropometric percentiles would behave on an assembly line. Being able to highlight any technical issues due to workstation organization even before having physical prototypes enables immediate action on workstation design while saving time and costs.

The system is designed to be integrated into an existing application that can recreate the movements performed by a human being sensorized with the XSens Awinda motion capture technology. The user performs work tasks on a real assembly line. The present work, on the other hand, aims to integrate a system capable of:

- simulate mannequins with different anthropometric percentiles;
- perform simulations on virtual lines through an immersive virtual reality visor.

This chapter aims to describe the functioning of the application developed and the logic behind the postural prediction system.

# 4.1 System Architecture

Several interconnected hardware and software components were necessary to achieve the goals. Hardware components include:

- Xsens Awinda Motion Capture: motion capture system based on inertial sensors;
- HTC- Vive pro: headset for virtual reality.

As a software component, however, there are:

- Xsens MVN: analysis software for the Xsens motion capture technology;
- Unity3D: game engine for video games, virtual and augmented reality applications.

A scheme of how the components interact with each other is shown in Figure 4.1. Xsens motion capture technology has many advantages including the easly interconnections with other systems such as Unity. Once the data are obtained, they are processed and extracted in .mvnx format, containing joint's rotation, and entered as input into the developed application. The movement performed by the user is then recreated in the Unity scene, and the position and rotation information of the hands, feet and head are extrapolated. This information is necessary for the correct functioning of the postural prediction system.

The workstation evaluation process may not require a visor, depending on if the simulation is performed on-site or virtually.



Figure 4.1: System architecture

#### 4.1.1 Motion capture system Xsens Awinda

The motion capture technology chosen is the Xsens MVN Awinda as it is easy to use and allows recording data quickly. It is based on 17 inertial sensors, each consisting of: 3D linear accelerometers to measure accelerations including gravitational acceleration, 3D rate gyroscopes measuring angular velocities, 3D magnetometers measuring the earth magnetic field, and a barometer to enable measurement of atmospheric pressure.

The trackers communicate via wireless connection with the receiver which is

connected via a USB port to the computer on which the licensed Xsens software is installed.

To avoid problems during the calibration phase and during the recording session, it is important to correctly position the sensors. The producers of Xsens explain the positioning of the trackers in great detail in the manual [74] but also via video tutorials. With the exception of the head sensor, which can be placed in any comfortable position, for the other sensors it is essential to refer to landmarks indeed easily accessible locations. The positioning of the motion trackers is described below, and a graphic scheme is provided in Figure 4.2.

- 1. Sternum motion tracker: in the middle of the chest;
- 2. Upper arm motion tracker: flat surface of the upper arm (lateral side above elbow);
- 3. Lower arm motion tracker: above the wrist;
- 4. Hand motion tracker: backside of hand and in the glove;
- 5. Shoulder motion tracker: scapula;
- 6. Pelvis tracker: flat on sacrum;
- 7. Upper leg motion tracker: on the top on the flat surface well above the knee;
- 8. Lower leg motion tracker: on top of the flat surface of the shin bone (medial surface of the tibia);
- 9. Shoe motion tracker: middle of bridge of foot under the shoe tongue;

Each sensor has a lithium-polymer battery, rechargeable via a docking station, with a nominal duration of 6 hours.

The Xsens MVN platform must be used to access the data transmitted by the sensors. This software allows the user to check the status of the trackers, their residual charge and the correct signal transmission to the receiver. Before starting the motion recording session, the measurements of stature, foot length and arm spam must be input. The system will automatically approximate the measurements of the other segments. Afterwards, you can proceed with a sensor calibration phase, which may be completed while standing in T-pose or N-pose, and consists of walking back and forward for 10s and trying to follow a straight line as closely as possible.

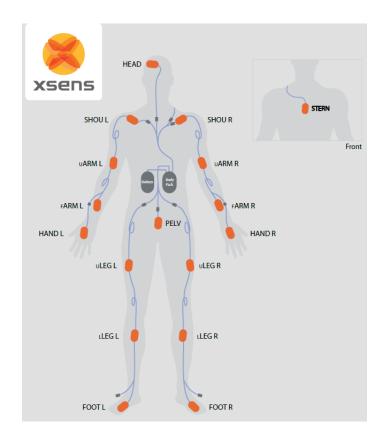


Figure 4.2: Positioning motion trackers: schematic representation of how the motion trackers should be positioned on the user performing the motion capture session

The integration of this system makes it possible to record the movements being performed, save and access them later. There are numerous data processing tools including the possibility of exporting data in different formats.

#### 4.1.2 HTC-Vive Pro

The technology used for virtual reality simulations is that of visors, in particular the HTC Vive pro. The system allows visual (lenses) and sound (headphones) interactions within a predefined physical space. Being combined with two controllers it is possible to simulate the action of grasping objects and thus hand-object interaction. The helmet can be adjusted to perfectly suit different users.



Figure 4.3: Visor HTC-Vive pro used for virtual simulations

## 4.2 User Interface

The graphical user interface developed for the device forming the purpose of this thesis will be described below. Once the system has been launched, the main menu, shown in figure 4.4, will appear. It is necessary to indicate, in the input mode section, the format of the file that it is intended to select. The choice is between a .mvnx and a .xml format. Once the file has been selected, it is possible to upload the video of the recording. Only when all options have been selected, the start button can be pressed and the system can be run. The second menu (figure 4.7) will be loaded, where on the left side the Final IK mannequin will be displayed, instead on the right the xsens mannequin will be displayed. In this menu there is the possibility to change the size of the xsens mannequin by clicking on the measure setup button instead, you can choose the percentile with which you want to do the simulation by clicking on the percentile button. If no percentile is selected, the system by default runs with the 50th percentile male.

By clicking on the Relative view button and selecting the absolute view option it is possible to change the camera orientation, in this way the correct view of both mannequins will be ensured.

The activation of the Direct Mode (described in section 4.4) requires clicking the appropriate button named *Direct Mode*. In this case, the options for activating/de-activating the effectors will appear (figure 4.6). If the toggle is not ticked then the effector will be disabled, so to enable it, it is necessary to tick the toggle of the respective effector. Once the effectors have been enabled you can select the effector you wish to move using the dropdown menu effectors and move it using the keyboard commands described in section 4.4.

<b>+ IMPRESSED</b>		
Configuration Info		
Input mode MVN Analyze File XML File path:		
Video Reference • No source • Video source	File Name (Optional):	
Source Editing <ul> <li>Use previous synchronization settings</li> <li>Change synchronization settings</li> </ul>	Start	
STELLANTIS	Politecnico di Torino H COMPETENCE INDUSTRY MANUFACTURING	
ي <del>مر</del> يد	u≪ <sup>4,2</sup> 4,0 Data Stream IP 1226a1	

Figure 4.4: User interface: main menu

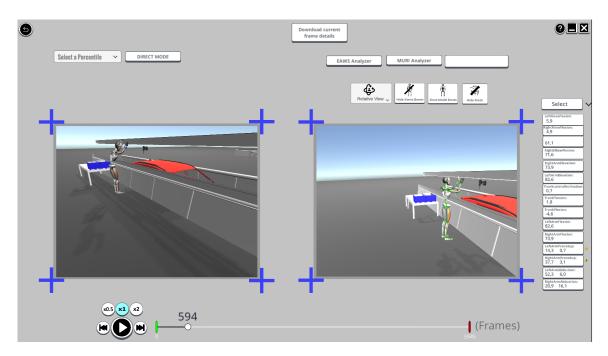


Figure 4.5: User interface: general layout of the application

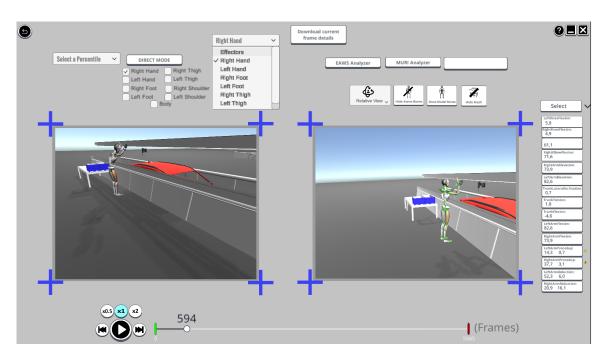


Figure 4.6: User interface: direct mode layout

# 4.3 System workflow

For the correct functioning of the system, it is necessary to have previously performed a motion capture session. After processing the data, it is feasible to replicate the user's motion on Unity and extract the position and rotation of hands and feet, and head's rotation for each frame. These input parameters are crucial for the successful execution of the postural prediction system that can be applied to mannequins with different anthropometric dimensions to estimate their behavior. Predicting the behaviour of several anthropometric percentiles is important to assess the reachability of all work points.

Alternatively, the system can work in direct mode in which the working points are given by the user via coordinates or by directly moving the end effectors using keyboard commands.

The application allows visualization of two mannequins, the first one replicates the motion using the information obtained from the motion capture session (will be referring to as the xsens mannequin) instead, the second mannequin is posed by the postural prediction system (will be referring to as the Final IK mannequin). Additionally, if a digital twin of the workstation examined has already been imported into the Unity scene, it is feasible to display it and t he system may detect potential collisions with objects and adjust the expected posture accordingly. A diagram of the general functioning of the application is shown in Figure 4.7.

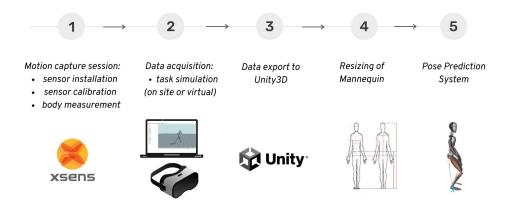


Figure 4.7: Descriptive diagram of the general operation of the system

#### 4.3.1 Data acquisition

An antecedent motion-capture step is required to be able to use the application. Xsens MVN Awinda equipment was used in this work. This tool has several advantages; in fact, the preparation phase in which inertial sensors need to be worn is very quick. Next comes the calibration phase, which may be completed while standing in T-pose or N-pose.

The mannequin can be parameterized by going to modify the anthropometric values in order to obtain a model as similar as possible to the user who is performing the motion capture session. This operation requires the measurement of the anthropometric values of the user.

Using Xsens MVN software it is possible to visualize user's motion and to record a session of the mannequin's movements. The data can be exported in .mvn or .mvnx format. The extracted information can be integrated into the Unity3D environment via the Xsens MVN Live Animation plugin; this tool allows for realtime reconstruction of the actor's animation within the Unity 3D scene. This information is used to animate the Xsens mannequin whose movemnts will be a faithful representation of the actual movements performed by the user during the recording session.

#### Virtual Workstation Model

In the case of simulations in virtual reality and not on site, it is possible to import a digital twin of the workstation into the Unity scene. However, in both cases, importing a virtual model of the workstation it is recommended to obtain a good representation of the motions executed. It is not essential that the model is perfectly faithful to the real one, but it is important that it is scaled so that the reachability of the workpoints and the correct posing of the mannequin can be properly verified. Having a scene in which the Final IK mannequin can move allows the obstacle avoidance system to function properly

Figure 4.8 shows the virtual model used in the simulation; it represents a car assembly line and was made in Blender [75].



**Figure 4.8:** Digital twin car assembly line: virtual workstation used for simulations in Unity

#### 4.3.2 Resizing of Mannequins

For the correct interpretation of the working points, it is essential to change the dimensions of the Xsens mannequin, otherwise the coordinates of the targets will not be congruent with reality. This occurs because the Xsens MVN Live Animation plugin is able to replicate the movement applying the rotation information, returned by the suit, to the joints; therefore it does not use the position information. Motion reconstruction will always appear natural, but by imposing the proper anthropometric measures of the user doing the recording, the precise coordinates of the working points may be obtained with a reasonable approximation. To scale the dimensions of the mannequin, the appropriate interface (shown in figure 4.9) was used, which requires the lengths (expressed in cm) of the bone segments to be inserted.

Measures must be taken in the correct way. For example, figure 4.10 shown how to measure the head and neck lengths. The correct way to obtain head lenght is to measure the distance between the highest point of the head and the centre of rotation of the neck. In general, it is important to refer to the centres of

Preset Values	Custom Values
Head 15,4 cm	<b>0.0</b> cm
Neck 9,4 cm	<b>0.0</b> cm
Shoulders Width 36,6 cm	<b>0.0</b> cm
Trunk Lenght 51,1 cm	<b>0.0</b> cm
Arm Lenght 30,7 cm	<b>0.0</b> cm
ForeArm Lenght 29,6 cm	<b>0.0</b> cm
Hips Width 14,1 cm	<b>0.0</b> cm
UpperLeg Lenght 41,7 cm	<b>0.0</b> cm
Leg Lenght 42,0 cm	<b>0.0</b> cm
RESET	UPDATE

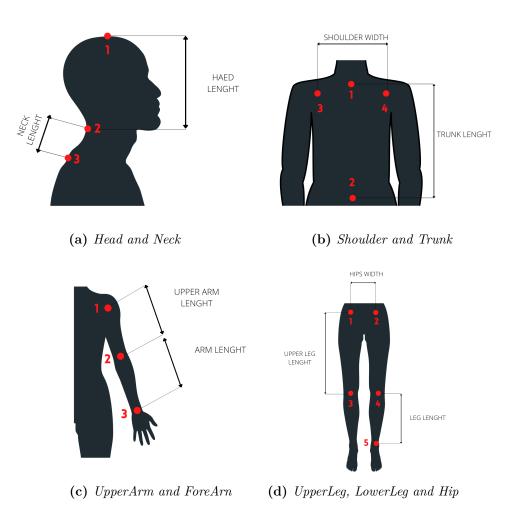
Design and Development

Figure 4.9: Interface to be used to manually change the size of the mannequin by inserting the values of the segment lengths

rotation of the joints in order to take measurements correctly. Therefore, during the measurement it is recommended to move the limbs to correctly determine the measuring points.

However, the approach for changing the dimensions of the Final IK mannequin is different; in this case, it is not necessary to manually enter all the segment lengths but is sufficient to select the type of anthropometric percentile, using the drop-down menu *Select a Percentile* (figure 4.5), with which the evaluation would be performed.

The system, once it is started, changes the size of the Final IK mannequin so that it is representative of the 50th percentile. This choice is due to greater use of this anthropometric percentile for ergonomic evaluations. In case other percentiles are of interest, a new percentile value cabe selected from the menu, thus calling



**Figure 4.10:** Methods to be adopted for the correct measurement of segment lengths

the SetPercentile() function. The function reads a file in .csv format in which all measurements of the 5th, 50th and 95th anthropometric percentiles for both men and female are saved (these measures are reported in Appendix A.1). These information have to be converted from mm to m and, in some cases, extra steps are required to obtain the useful value to change the dimensions. While the system implemented in Unity requires a certain type of input information, the normative about the anthropometric measurements returns others. For example, from the normative [38] we get the value of stature which goes from head to toe, while in our application the value of trunk length must be entered. This, fortunately, can be obtained by subtraction to the stature value, the length of the legs, head and neck.

#### 4.3.3 Pose Prediction System

In order to use the postural prediction system the FBBIK requires an initialization phase that consists of the following steps:

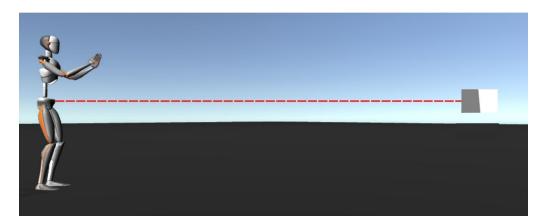
- 1. Assigning the targets to their respective effectors;
- 2. Definition of the kinematic chains;
- 3. Setting of Spine Stiffness, Pull Body Vertical, Pull Body Horizontal, Iterations and IKPositionWeight parameters;
- 4. Setting limb orientation to achieve rotations that are physiologically correct.

These initialisation steps are performed automatically by the system when the framework starts. These commands can be accomplished either by using the Unity3D editor or via script. It was preferred to proceed via script in order to make the system more easily transferable. This will ensure, in the future, the possibility of integration with other applications and the possibility of changing the mannequin model.

Afterwards the initialisation phase, the information of position and rotation of the target points are taken for each frame and they are used as input parameters for the *PoseMannequin()* function. For each frame, this function first translates the input data so that the two mannequins are not displayed superimposed. Then it assigns the new position and rotation information to the FBBIK targets, activates the weights and returns an initial estimation of the DHM's posture.

However, to have a realistic posture, it's not sufficient only locate the targets but are required additional functions for the management of head rotation and spine rotation. To handle spine rotation, the GameObject.Transform.LookAt() function implemented on Unity was used. This function ensures that the forward direction of the GameObject always points to the target which position is adjusted to ensure that the mannequin always face the hands targets.

A similar approach has also been used to handle head rotation. Instead, in this case the head rotation data given by the Xsens suit is used. Unfortunately, because the FBBIK does not allow to rotate segments that are not end-effectors, this information cannot be used directly. It was necessary to define a target for the head and moving it in the space in order to generate the expected rotation of the head.



**Figure 4.11:** Rotate spine function: example of the target position of the LookAt() function

A general diagram of the functioning of the postural prediction system is shown in figure 4.12

#### **Definition of Ergonomic Postural Rules**

The Final IK tool is designed to work in gaming and so returns a natural pose that may not be the ergonomically optimal pose for performing the action of interest. To overcome this limitation, working in synergy with experienced ergonomists in Stellantis, a set of postural rules was designed to achieve a pose that was as ergonomic as possible.

The rules implemented are empirical because they are based on observations of how a movement should be performed. Picking up an object from the ground, for example, is the action that is generally erroneously performed by most people because they bend the back. This is an incorrect action; experts recommend bending the knees and picking up the object to reduce back stress.

During the step of developing postural rules, the main focus was on the standing workstation, as the one widely used in assembly lines in the automotive field. The use of these postural rules, in the postural prediction system, is accomplished by the the implementation of control functions based on the target's position.

An initial check is made on the Y coordinate of the target (height) in order to evaluate the necessity of bending the knees by 60 degrees. If the target coordinate is lower than the knee height then a knee flexion of 60 degrees is set.

Unfortunately, using FBBIK tool it's not possible to directly rotate the knees because they are not considered as end-effectors, however, several strategies could be implemented to make the knees flex. A first solution was to define bend constraints for the left and right leg kinematic chains. In this way, the limb could

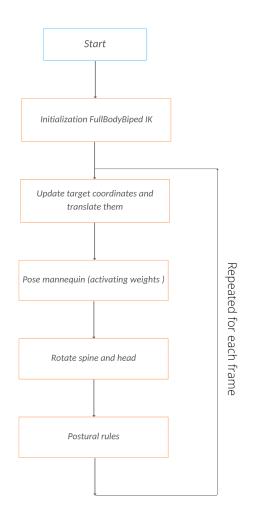
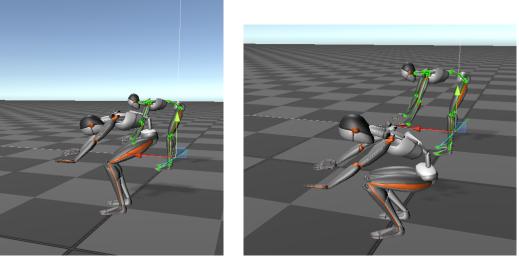


Figure 4.12: Diagram *PosePrediction()* function

be bent in the direction from the hip to the bend goal. However, it is not enough to apply the rotation to the bend goal to have the same rotation on the kinematic chain, but the bend goal must be shifted appropriately. This strategy was complex to implement since a new bend goal position had to be calculated each time the knees should be bend.

Therefore, it was decided to adopt a different strategy that would allow the knees to be easily flexed while being functional and scalable for all anthropometric percentiles. The idea is to achieve knee flexion by lowering the pelvis position of the mannequin. Using the *positionOffset* function, implemented in the FBBIK tool, it's possible to define an offset, depending on the angle at which I want to bend the knees, to change the body effector position at each frame.



(a) Postural prediction without constraints on position (b) Postural prediction with constraints on position

**Figure 4.13:** Comparison of postural prediction without ergonomic rules (a) and with ergonomic rules (b)

#### **Obstacle Avoidance**

Unity3D offers the opportunity to easily manage collision between objects in the scene, taking advantage of a number of functions already implemented and previously explained in the section 3.4.2.

These features made it possible to manage the obstacle avoidance system. It is necessary to add the collider component to each object in the scene.

The geometry of the collider must be representative of the encumbrance of the object for example, for barriers or objects belonging to the workstation, usually the use of box colliders is optimal. Instead, cylindrical colliders have been used to represent the encumbrance of the user.

The colliders of the DHM are relocated at each frame, taking into account how the mannequin moves within the scene and thus the working points. In addition, when the anthropometric percentile is changed, the colliders are also resized. With these two strategies, the collider is always faithful to the structure of the mannequin.

The algorithm implemented in *ObstacleAvoidance.cs* exploits the *OnTriggerEnter()* function to intercept the collision between the mannequin and any *GameObject* with a Collider Component added and in which the *IsTrigger* option is checked.

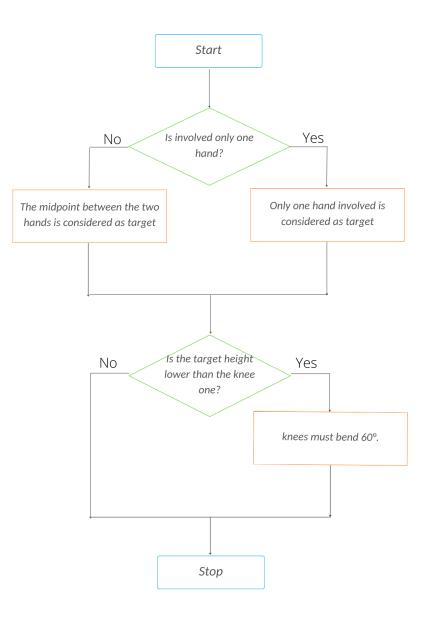


Figure 4.14: Diagram on the postural rule for bending the knees

When the function is called means that the mannequin is in collision with another object. Depending on the tag attached to the *GameObject*, different strategies are implemented to handle the obstacle.

The system can handle two different types of obstacles

1. Barrier: it refers to any vertical obstacle;

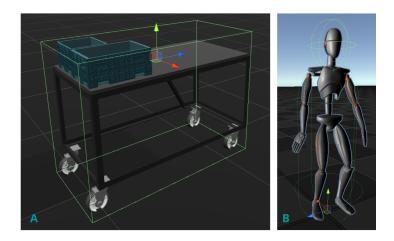


Figure 4.15: Collider component attached to an object of workstation (A); collider component attached to the DHM

2. Shelf: it refers to any horizontal obstacle;

If the mannequin collides with a barrier, the distance between the midpoint of the feet and the collision point is calculated. This distance value is used to move back (relative to the obstacle) the foot targets and thus move the mannequin backward. Instead, when the mannequin collides with a shelf, the algorithm estimates the distance between the mannequin's stature and the shelf's height. This distance value is used as input parameter in the *positionOffset* function in order to lower the pelvis position of the mannequin.

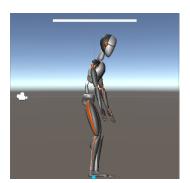
These methods are based on the use of the OnTriggerStay() function, which implies that the collider positions remain unchanged. As a result, the collision may be detected throughout the activity and the appropriate intervention can be made.

The operating logics are described below. The benefit of using a structured algorithm is to easily include new checks on the gameObjects's tags, thus being able in the future to handle more obstacles.

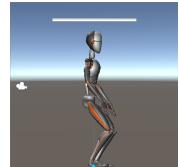
#### 4.4 Direct Mode

In addition to postural prediction mode, the application allows the user to operate in a direct mode, in which it is the user that moves the effectors. It's possible to activate the effectors of the hands, feet, hips, shoulders, all for both the left and right sides, and also the pelvis. All effectors may be triggered separately or simultaneously, but to move them, you must choose one at a time and use keyboard instructions to move it.

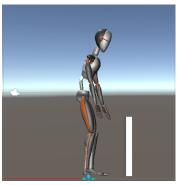
The commands for moving an effector are described below:



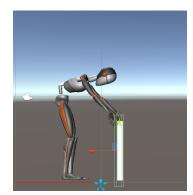
(a) No collision



**(b)** Collision detected with a shell



(c) No collision



(d) Collision detected with a barrier

Figure 4.16: Example of obstacle avoidance system

- W: moves the effector forward
- S: moves the effector backward
- A: moves the effector to the left
- S: moves the effector to the right
- Q: moves the effector down
- E: moves the effector up

Alternatively, the user can enter the information of position and rotations of the target that the end effector has to reach.

This mode is helpful in two circumstances: the first is when you don't have data from motion capture with Xsens technology and need to position the mannequin;

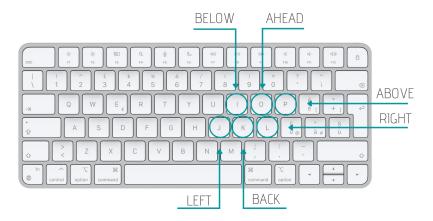


Figure 4.17: Keyboard commands

the second is to adjust any pose predicted incorrectly by the postural prediction system.

# Chapter 5 Test and Results

After verifying the general accuracy of the application and its functionality, the validation phase of the postural prediction system has proceeded. Initial experimental trials were conducted using MVN software and the Xsens Awinda motion capture system and two different tasks were analyzed. The first recording session was conducted in a laboratory built specifically for ergonomic simulations. The task consisted of the application of seals to the front and back car doors. The purpose of this test was to analyze the altimetry of the structure and thus assess whether the set height allowed all points to be reached. This recording was made on physical prototypes already in the laboratory.

Later test sessions were performed at Competence Industry Manufacturing 4.0, which provided an HTC-Vive visor to recreate a car assembly line and perform a simulation without physical prototypes so working only in a virtual environment. The use case is to test the design of a car assembly line, making sure that the work-points are adequately reachable by several anthropometric percentiles. It was decided to conduct the motion capture recording sessions with users representing different percentiles to highlight critical issues in the prediction system. While the application is running, the system performs a first check on the physiology of the predicted pose. Next, it was decided to evaluate how much the addition of postural rules would allow for an ergonomic posture and how strong the postural prediction system was as percentiles changed.

### 5.1 Postural Analysis

To ensure that the system could return physiological positions in most cases, postural angles were calculated. Reported below are the calculated angles:

1. Left and right knee flexion: the angle between the upper and lower leg segments. A fully extended knee corresponds to an angle of 0, generally, there

is a maximum rotation of  $120^{\circ}$ ;

- 2. Left and right elbow flexion: the angle between the upper and lower arm segments. A fully extended elbow corresponds to an angle of 0, generally, there is a maximum rotation of about 180°;
- 3. Left and right arm angle: the angle between the upper arm and trunk segment (neck pelvis distance);
- 4. **Trunk lateral inclination**: corresponds to the inclination angle of the trunk segment (neck pelvis distance) relative to the frontal coronal plane of the manikin;
- 5. **Trunk torsion**: the angle between the segment connecting the hips and segment connecting the shoulders;
- 6. **Trunk flexion**: the angle between the trunk segment (neck pelvis distance) and the foreword direction;
- 7. Left and right prono-supination: Pronation supination is the rotation of the wrist around the axis of the forearm;
- 8. Left and right arm flexion: the angle between the arm segment (shoulder hand distance) and the trunk segment (neck pelvis distance);
- 9. Left and right arm abduction: the angle included among the upper arm segment projected on the frontal plane and the neck-pelvis segment projected on the same plane.

The method used to calculate the angles is the geometric one based on the API game-engine in Unity3D. The idea is to calculate the angle between two segments; in fact, if we consider the knee flexion angle, this requires the thigh and leg segments to be calculated. The first segment is obtained by subtracting the hip position from the knee position, while the second segment is obtained by subtracting the knee position from the ankle position. The angle formed by two segments P1 and P2 is reported in the equation 5.1:

$$\cos(\theta) = \frac{\boldsymbol{P1} \cdot \boldsymbol{P2}}{|| \boldsymbol{P1} || || \boldsymbol{P2} ||}$$
(5.1)

At each frame, all angles are calculated and checked to make sure they are within the validity ranges. These ranges were obtained by comparing with experienced ergonomists in the field and also referring to the joint kinematics literature. The ranges considered physiological are given in appendix A.2. Performing a postural analysis at each frame made it possible to verify if the pose is physiological and extract any incorrect poses that might be adjusted using the Direct Mode (described in section 4.4) or compared with other postural prediction systems.

When a critical posture is detected, the distance and height information of the target (calculated with respect to the root of the DHM) is saved to a txt file which is automatically updated by adding a line. Below an example of a line that is added to the end of the text file when a problem is found with knee flexion.

« New Critical Pose, problems with KneeFlexion ; angle: 200° RIGHT HAND, CoordinateX: 50 cm ; CoordinateY: 40 cm ; CoordinateZ: 30 cm LEFT HAND, CoordinateX: 50cm ; CoordinateY: 40 cm ; CoordinateZ: 30 cm»

The percentage of critical poses detected by submitting the system to multiple simulations is low and is about 0.26% out of more than 23000 frames analyzed. This is supported by the fact that FBBIK tended to be an inverse kinematics component used primarily to animate human bipedal models and hence provides reasonably physiological poses.

## 5.2 Accuracy of postural prediction system

In order to assess the robustness of the postural prediction system as the percentiles varied, several simulations of the same task were carried out but with users belonging to different anthropometric percentiles. The users selected were people inexperienced in the field of ergonomics, so they performed the movements without any information on the best way to approach the target.

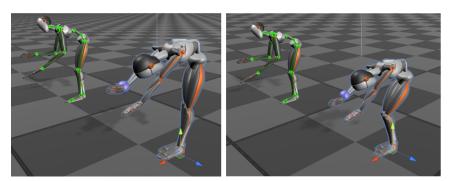
The tests aim to assess two different circumstances. The first one concerns the initialisation of the parameters of the *FullBodyBipedIk* components and with a particular focus on the reach parameter of the kinematic chains of the legs and arms and parameters such as spine stiffness, pull body vertical and horizontal.

Another focus point during the tests was the effectiveness of the system in predicting the postures of different percentiles. In this case, it was decided to compare the postural predictions of 50th female, 5th female, 95th female and, male based on the recording made by a 50th percentile male user with the recordings made by users belonging to the corresponding percentiles.

### 5.2.1 Solver parameters validation

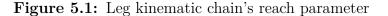
The definition of the parameters was done qualitatively, evaluating the combination that achieves a posture as close as possible to the desired one.

For the evaluation of the parameters, the postural prediction was conducted with



(a) leg kinematic chain reach parameter disable

(b) leg kinematic chain reach parameter enable



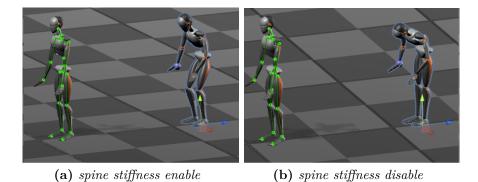
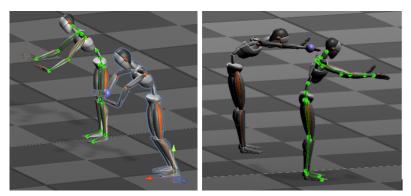


Figure 5.2: Spine stiffness parameter

the nearest percentile to the user performing the simulation. Specifically, the 5th, 50th, and 95th percentiles for males and females were considered.

A high **reach** value (around 1) defined for the arm's kinematic chains is useful when the task requires greater attention from the worker, and therefore the user needs to get closer to the target. When, on the other hand, precision is not required to perform the task, lower values (around 0.1 - 0.3) can be opted.

Concerning the kinematic chains of the legs, even low reach values (around 0.1) are sufficient for the DHM to assume a posture with bent legs. It is advisable to always have values equal to 0 otherwise there is a risk of always having a posture with slightly bent legs. There are situations, such as the one shown in figure 5.1, that having a reach value greater than zero, even if it is low, can give a more realistic pose. Enabling the reach parameter can be useful to handle cases where the postural rule on knee flexion does not intervene that is when the target is below the spine but above the knees. The **pullbody vertical** parameter has a



(a) pullbody horizontal enable (b) pullbody horizontal disable

Figure 5.3: Pull body horizontal parameter



(a) Virtual simulation of a(b) postural prediction of the user screwing screwing task

Figure 5.4: Example of the screwing task: comparison between postural prediction and motion capture

similar action to the reach parameter defined for the leg kinematic chain, the only difference is that pullbody acts on the whole body instead of on individual chains like the reach parameter does.

The **spine stiffness** parameter allows the stiffness of the back to be controlled. A high value indicates that the back will be stiffer than a low value. The manufacturer recommends, if you have no specific requirements, to have a value close to 0. However, varying this parameter can be useful to position the mannequin in the desired way. Figure 5.2 clearly shows the effect of this parameter on the returned

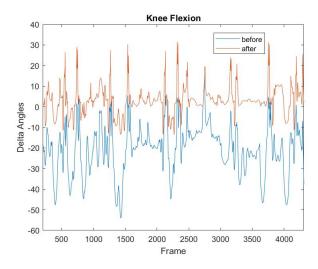


Figure 5.5: The trend is the angle difference between the postural prediction output before and after parameter optimization. The example shows the output of the 95th female percentile but a similar pattern was also found for the other percentiles analyzed. After optimisation of the parameters, a lower difference can be observed.

pose. When the stiffness is 0, the mannequin will bend the back to achieve the target, instead, if the stiffness is higher, the mannequin will bend the knee with a straight-backed.

The last parameter analyzed is the **pullbody horizontal**, a value even slightly greater than 0 makes the returned posture more pulled horizontally. This strategy was not found to be efficient, as it often leads to unrealistic outputs, as shown in figure 5.3.

A critical posture emerges during the screwing phase, which is illustrated in figure 5.4. The posture returned is unrealistic. The solution can again be found in the initialization parameters of the system. Increasing the reach parameter for the kinematic chain of the arm (in this case left) by a large amount results in a more realistic predicted pose. It was verified, however, that using this strategy for the entire recording leads to a higher number of incorrectly predicted poses by the system.

After an initial qualitative analysis of the parameters, it was decided to verify the improvement in the returned posture. With the adjustment of the parameters, there is an improvement in the prediction of the lower limbs as demonstrated in Figure 5.5 in which it's shown the trend of the angle difference between the postural prediction output before and after parameter optimization. After optimisation of the parameters, a lower difference can be observed. The example shows the

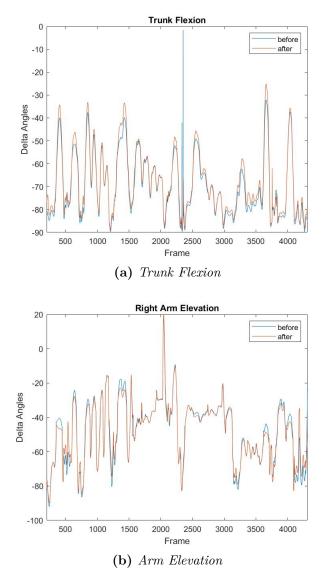


Figure 5.6: The trend was approximately similar before and after parameter optimisation. The example shows the output of the 95th female percentile but a similar pattern was also found for the other percentiles analyzed.

output of the 95th female percentile but a similar pattern was also found for the other percentiles analyzed. However, there is no effect with the management of the trunk flexion in which the trend was approximately similar before and after parameter optimisation. The example in Figure 5.6 shows the output of the 95th female percentile but a similar pattern was also found for the other percentiles analyzed.

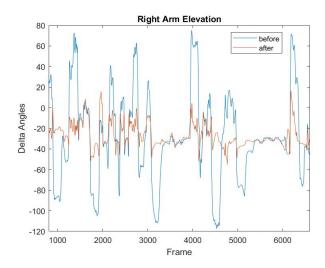
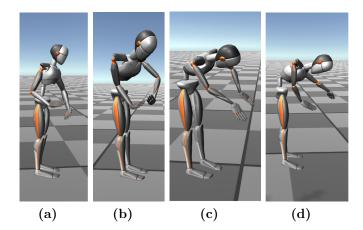


Figure 5.7: Arm elevation 5th percentile: improved prediction of the upper limbs observed only for the 5th percentile



**Figure 5.8:** Comparison between: Motion Capture 5th percentile(a); Pose predicted of a 5th percentile from a 5th percentile motion capture record (b); Pose predicted of 5th percentile from a 50th percentile motion capture (c); Pose predicted of 5th percentile from a 95th percentile motion capture (d)

An improvement in upper limb prediction was found only for the 5th percentile, for all other percentiles the pattern before and after parameter optimization showed no improvement.

#### 5.2.2Validation with different percentiles

After completing the first test phase in which the best combination of parameters was identified, the next step was to evaluate the effectiveness of the postural prediction system on different percentiles.

To accomplish that aim, the joint angles returned by the posture prediction system were compared to the angles returned by the motion capture system. Postures were predicted from both the 50th percentile male and 95th percentile male data.

A more focused analysis was carried out thus only the most relevant postures in the task performed were considered. For each posture, the joint angles were compared. The postural prediction system returns approximately the same posture even if the recording is made from the 5th, 50th, or 95th percentile, the output is influenced by how the user performs the simulation. In this example, the 95th subject grasps the screws going deeper and further than the 5th percentile does.

Investigating several tasks revealed that the postural prediction system leads to outputs in which the mannequin always has a bent back. Observing the graphs in figure 5.9, it can be seen that the trunk flexion angle has greater values in the case of postural prediction than in the motion capture. This occurred with both postural predictions based on recordings made from the 50th percentile and recordings made from the 95th percentile. To reach targets that are far away, from the motion capture sessions it emerged that a subject tends to bring the pelvis forward a little instead of fully bending the back which instead, which the postural prediction system does. This is why there is a significant difference in the trunk flexion angle between the motion capture session and the postural prediction system. There was no improvement by increasing the pullbody horizontal parameter, the returned pose was rather unrealistic.

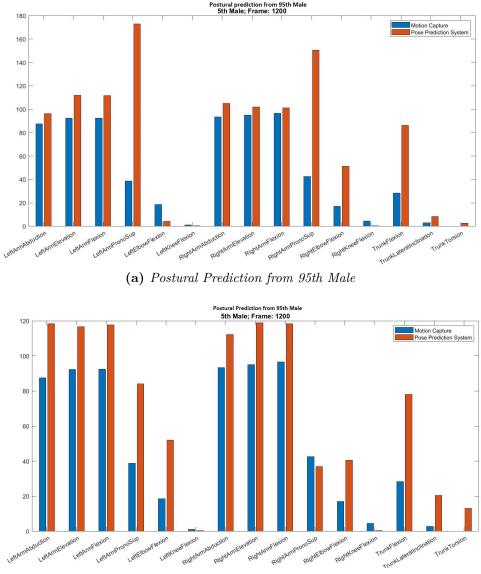
Just the example of one task has been given but this trend is found in the performance of many tasks.

Further differences were noted in arm prono-supination and elbow flexion angles. This can be explained because the strategies by which a target can be reached are different. The example in figure 5.10, shows that both postures are physiological since the target can be reached in both ways. This problem implies the necessity to add postural rules to handle DHM positioning correctly and in the desired way.

#### 5.3Accuracy of obstacle avoidance system

The validation of the obstacle avoidance system was accomplished by providing the target coordinates because no simulation performed was able to create a condition in which there was a collision with an item belonging to the workstation. It was therefore decided to test the case of an employer working on car's underbody.

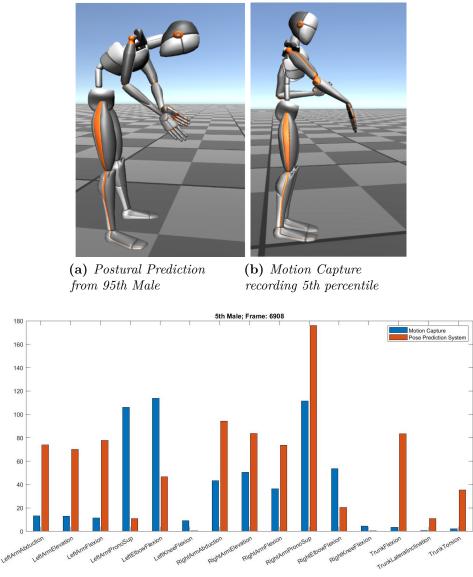
The system has been successfully demonstrated to detect collisions with other



(b) Postural Prediction from 50th Male

Figure 5.9: Comparing the joint angles returned by the motion capture session performed by a 5th percentile and the joint angles returned by the postural prediction system on the 5th percentile from data taken from the 95th percentile (a) or 50th percentile (b) recording sessions

objects, and the strategies adopted for obstacle management are functional. It occurred that, in the case of items belonging to the workstation, it is not crucial that the collider accurately replicate the geometry of the object, but that it can approximate their encumbrance. Generally, simple geometries such as boxes,



(c) Joint Angles

**Figure 5.10:** Comparison between the pose of a 5th percentile predicted by the postural prediction system from a 95th percentile (a) and the task performed by a 5th percentile (b). Image (c) shows the angle values of the postures from the motion capture and the postural prediction system

cylinders, and spheres successfully fit the requirements.

However, an opposite conclusion concerns the definition of colliders for DHM. In this case, to have realistic results, the colliders must be much more reliable and

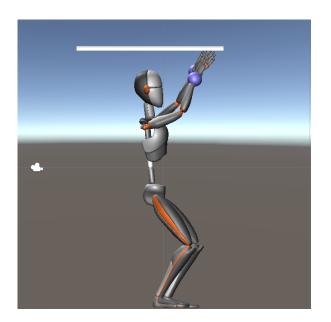
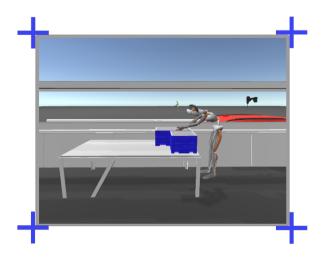
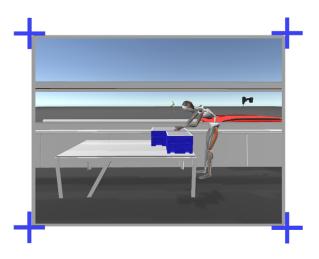


Figure 5.11: Example of an employer working on car's underbody

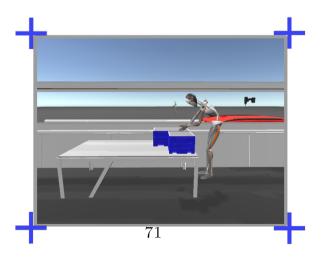
faithful to the real dimensions of the model. This is particularly true if the obstacle is a barrier; when, on the other hand, an obstacle is a horizontal object, collider definition is easier.



(a) 5th male percentile postural prediction from 50th male



(b) 50th male percentile postural prediction from 50th male



(c) 95th male percentile postural prediction from 50th male

**Figure 5.12:** Postural prediction comparison of the same task performed by the 5th (a), 50th (b) and 95th (c) percentiles from the motion capture recording made by the 50th percentile male.

# Chapter 6 Conclusion

The present work attempted to make a contribution to DHM-based systems for ergonomic evaluation. In particular, by developing a postural prediction system that was able to predict the behavior of different anthropometric percentiles in a workstation.

To this end, the great potential of Industry 4.0 technologies, in particular virtual reality and motion capture, were exploited to design human-centred work environment.

The developed application can predict, from motion capture data, the movements of a user with different anthropometric parameters from the one who performed the recording. The aim was to recreate physiological movements and verify that a workstation could be suitable for different percentiles thus that all the work points could be reached.

The results revealed that the pose returned by the system is physiological even if it does not coincide with the movements performed by the users during motion capture sessions. Several strategies can be adopted to perform a task and indeed the inverse kinematics problem has almost more than one possible solution. The main complexity of the postural prediction system lies in the indeterminacy of the inverse kinematics problem which, in this circumstance, can be solved by introducing constraints due to the nature of the movements performed but also due to the workstation organization. The constraints given by the nature of movement refer to the implementation of several postural rules based on how an action should be performed from an ergonomic point of view. For example, the rule of bending the knees to pick up an object from the ground is useful but it is not enough to provide correct postures. Therefore, several postural rules, consistent with the intended purpose, should be added.

Whereas constraints related to workstation organization refer to the presence of obstacles that, somehow, determine constraints on posture.

The system was fortunately implemented taking into account the possibility of

handling more obstacles in the future as well as the addition of more postural rules based on the observation of how an action should be performed.

Another critical issue that has emerged in the postural prediction system is in the prediction of tasks that are performed with only one hand; to obtain a more accurate prediction, it is recommended to perform the recording making sure to keep both hands at the same height.

Contrary to the systems developed so far that are quite sophisticated and need extensive training, this framework is simple-to-use and required only low training. It's a support for the ergonomist because can highlight any technical issues caused by workstation organization, before producing any physical prototypes. Thus, allowing for faster intervention in the workstation design while saving time, cost, and resources.

## Appendix A

## A.1 Anthropometric measurements

	5-Male	5-Female	50-Male	50-Female	95-Male	95-Female
Stature	1638,66	1520,239	1755	1626	1871,34	1730,351
Cervical-Clavicular	51,59	46,58986	53	48	55,12	50,11522
Shoulder width	331,21	289,092	358	318	391,84	340,5623
Shoulder - Elbow	255,73	242,8478	279	264	302,27	274,5761
Elbow- Wrist	240,78	217,7833	257	234	268,99	243,166
Pelvic link	81,95	83,94927	89	91	94,64	96,64059
Cervical - Pelvis link	402,85	372,7833	424	389	463,48	417,908
Hip- Knee	397,21	362,7971	424	391	454,32	417,7928
Knee- Ankle	387,45	351,5667	422	384	446,68	407,2674
Ankle Height	70,42	66,94927	81	74	90,17	81,05073
Hand grip	71,06	66,06449	76	71	81,64	80,16595
Hips width	150,33	168,4884	132	184	175,71	193,871
Cervical- Head	298,78	282,1935	315	297	322,05	309,6913

## A.2 Joint angle range

Angle	Min Value	Max Value
Knee Flexion	0.51	137
Elbow Flexion	0	140
Arm	0	180
Trunk Flexion	-90	20
Trunk Inclination	-75	75
Trunk Torsion	-50	50
Arm Prono-Supination	0	270
Arm Flexion	0	180
Arm Abduction	0	180

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