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Coordinator: Prof. Francesco Garofalo

HuPOSE : Human-like posture generation and biomechanical analysis for human figures

Luigi Pelliccia
luigi.pelliccia@unina.it

Thesis Supervisors:
Prof. Luigi Villani
Prof. Giuseppe Di Gironimo

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to my parents, to my sisters and to Angela

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Summary

Over the years an increasing attention has been devoted to ergonomic analyses even from the early stage of the design process. Ergonomic and human factor evaluations often require building a physical mock-up in order to provide an assessment of discomfort and ease of use. This process, using traditional methods, is very time demanding, especially when the design has to be modified and revalidated. Digital mock-up instead, enables manufacturers to design digital prototypes of a product in full details, simulating its functions and predicting interaction among its different components.

In order to take advantage of digital simulation to conduct ergonomic assessments *digital substitutes* of human beings (also called digital humans), able to interact with the digital mock-up in simulation environment, are required. Since these digital humans are required to simulate human beings in digital environments their resulting movements must be as *human-like* as possible. Although these digital human simulation tools are now advanced enough to correctly predict human-product and human-process interaction, even before a physical prototype is constructed, the animation process is still very time demanding, mainly because it still relies on key frame techniques.

Moreover, the accuracy of the resulting simulations are strongly related to the experience of the operator. The aim of this thesis has been to develop an algorithm capable of speeding up the animation process of digital humans. An algorithm capable of conducting biomechanical analyses has been developed as well.

Chapter 1 provides a general introduction underlining the need to use digital human simulation tools from the early stage of the design process. The main applications of digital technologies in industrial world are presented as well.

Chapter 2 provides an overview of the the main digital human simulation tools currently available, highlighting their advantages and disadvantages.

Chapter 3 describes the mathematical theory underlying the developed *HuPOSE* model. Both the kinematic and the biomechanical model are presented. The main contribution is the formulation of the inverse kinematic problem in terms of a single CLIK algorithm, using an *Augmented Jacobian* matrix. This approach suggested also the possibility of computing the static torques at the joints of a digital human by means of *kineto-static duality*. The computation of the static torques allowed to conduct a biomechanical analysis, in reference to a load-lifting task, very easily.

Chapter 4 discusses several possible application for the developed *HuPOSE* model. Simulation in virtual environment have been conducted using *Matlab–Simulink* in order to show the ease of motion planning for a human figure. The implemented whole-body motion control technique takes into account the position of the centre of pressure of the digital human. This technique allows to achieve quite natural movements in spite of the limited number of task related control points considered. A biomechanical analisys is presented as well, whose results are results are in good agreement with literature data.

Chapter 5 contains the main results achieved, remarks and proposals for future development

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Acronyms

BTK biomechanical toolkit

CLIK closed-loop inverse kinematics

CoM centre of mass

CoP centre of pressure

DH Denavit–Hartenberg

DHM digital human modelling

FK forward kinematics

DoF degree of freedom

FPS frames per second

IK inverse kinematics

IR infrared

KSD kineto-static duality

MOCAP motion capture

PLM product lifecycle management

UCD user-centred design

VEE virtual end-effector

VR virtual reality

VRML virtual reality modelling language

Chapter 1

Introduction

Over the years, manufacturing companies have taken the "man adaptability" as a basic parameter of quality for their products and manufacturing processes. This trend has led to review the design approach, giving to the end-users' needs, wants, and limitations an extensive consideration. Thus, an increasing attention is devoted to ergonomics and human factors evaluations even from the early stages of design process [2, 3, 4]. This approach is known as user-centred design (UCD) [5]

Ergonomic and human factor evaluations often require building a physical mock-up in order to provide an assessment of discomfort and ease of use. This is a very time demanding process, especially when the design has to be modified and revalidated. Digital mock-up provided by computer-aided engineering applications, instead, enables manufacturers to design a digital prototype of a product in full details, simulating its functions and predicting interaction among its different components (Figure 1.1). The production of physical prototypes, than, is deferred to the final stages of the design process [6].

In order to take advantage of digital simulation to conduct ergonomic assessments (computer-aided ergonomics) *digital substitutes* of human beings, able to interact with the digital mock-up, in simulation environment are required.

Indeed, the availability of such *digital human simulation* tools, beside digital mock-up, allows to evaluate human-product and human-process interaction even before the physical prototype is available. Figure 1.2 shows an example of ergonomics assessments concerning vehicle interior design (reach, visibility and comfort).

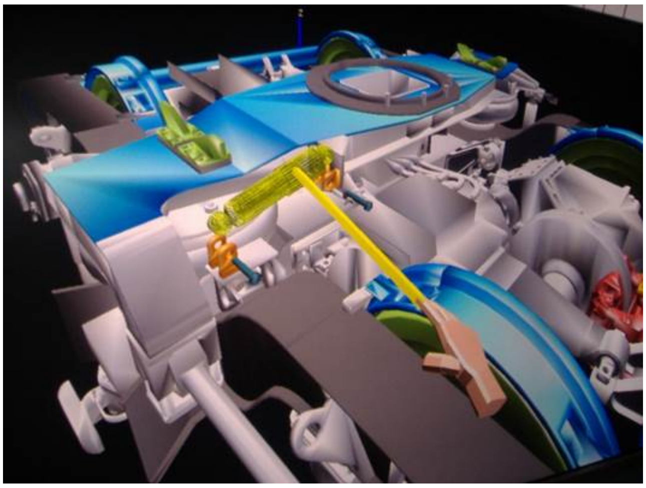


Figure 1.1: Assembly simulation of a bogie using a digital mock-up in virtual reality.

Figure 1.2: Vehicle interior design using Jack^{TM} digital human simulation tool.

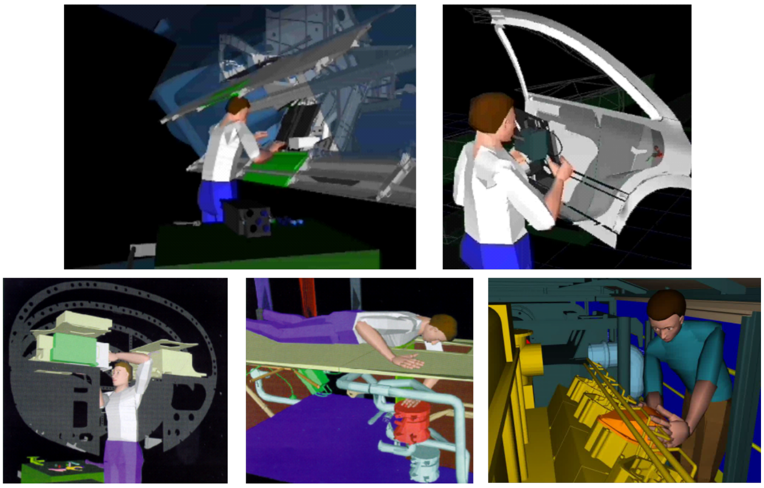


Figure 1.3: Accessibility and maintainability assessments using Jack™ digital human simulation tool

Digital mock-ups, together with digital human models, are increasingly used in order to reduce the development time and cost, as well as to facilitate the prediction of performance and/or safety [7]. Digital humans have also been implemented in product lifecycle management (PLM) software in order to improving product development and controlling process of product design and analysis, e.g. digital human simulation tool JACK™ is a part of a SIEMENS PLM product solution package.

The ergonomic design methodology relying on digital human models makes the iterative process of design evaluation, diagnosis and revision more rapid and economical [8], increasing the quality by minimizing the redundant changes and improving safety of products by eliminating ergonomics related problems. For example, Jack™ human simulation solution was used to evaluate ergonomics and worker safety in installing a new satellite digital antenna radio system at *Ford Motor Co.*. This analysis occurred at the product design review stage. This allowed reduce the late design modification efforts and helped assess performance and ergonomics based problems prior to prototyping [9].

These digital humans, provided by many process simulation software, are essentially kinematic chains consisting of several segments and joints (Figure 1.4). The lengths of their segments, as well as their mass distribution, are derived from anthropometric databases, e.g. [10, 11, 12, 13], which can

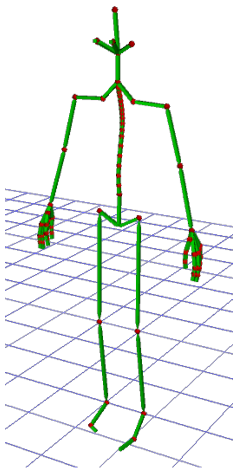


Figure 1.4: Skeleton of Jack™ digital human.

be queried with respect to different percentiles in the population.

Commonly, two human model generation methods are implemented in digital human simulation systems: percentile and custom-built.The first method enables the user to generate percentile human models for different genders and age groups using anthropometric database. The latter method, on the other hand, enables the user to create “tailor-sized” human models, specifying a set of anthropometric dimensions. The missing values of anthropometric dimensions are estimated by means of regression equations incorporated in the simulation system. For example, the boundary manikin methods [14, 15, 16]and distributed methods [17, 18] belong to the custom-built method of digital human models generation because the body segment sizes of each selected representative case should be manually specified in a digital human model simulation system.

The great deal of research conducted over the years, in order to meet the ever-growing demand for such simulation tools has given birth to the DHM, which led to the development of several software tools [19, 20, 21], whose main goal has been to reproduce as closely as possible the human behaviour in simulation environments.

In order to provide a realistic human simulation, digital humans must behave like human beings not only in terms of anthropometry but also in terms of motion. Namely, once a simulation of a planned task is conducted, the resulting movements of the digital humanoid must be *as human-like* *as possible*. This latter issue is still a key factor in modern digital human simulation tools. In fact, even though virtual prototyping and DHM software tools are advanced enough to correctly predict human-product and human-process interaction, digital human simulation, and consequently the so-called "process simulation", often becomes a very time-consuming task, mainly because of the difficulty in controlling and generating the whole-body motion for digital human figures.

Indeed, this process is still tied to key-frame[1]-based animation techniques [22] which makes the generation of motion of a complex kinematic chain, such as a human figure, very time demanding[2]. In addition, the accuracy of the resulting simulations are strongly related to the experience of the operator. Even though these software tools implement inverse kinematics (IK) algorithms, they generally manage only a limited number of links at time.

Providing simulation tools capable of generating human-like movements has an immediate and objective reason. In fact, as it will be exposed in Chapter 3.2, the results provided by ergonomics and biomechanical assessments are referred to the specific posture taken by the operator (e.g. load-lifting, comfort). Thus, predicting an incorrect posture will affect the results of the analyses. Briefly, an incorrect posture prediction leads to incorrect biomechanical and ergonomic analyses results. Furthermore, the need to provide movements as close as possible to those of human beings is inherent in the concept of simulation itself.

The developed *HuPOSE* [3] algorithm aims at filling the existing gap, providing a tool capable of considerably speed-up the posturing of human figures. Indeed, the algorithm enables to generating human-like postures for human figures[4] by means of limited number of task-related control points.

[1]Key-frame is an animation technique which consists of assigning, once defined the start and the point of the animation, a posture to the digital human for each frame. In between frames are interpolated in order to obtain the whole animation. It is worth to highlight that the posture for each frame is generally assigned "by hand", namely using forward kinematics (FK) techniques. In such a way the operator controls each joint of the kinematic chain in order to achieve the posture for the humanoid

[2]The animation process may take hours, or even days, of work.

[3]Human-like posture generation and biomechanical analysis for human figures.

[4]Sometimes the terms *digital humanoids* (or simply humanoid), as well as *virtual manikins* are used instead of *human figures*. Although each term is related, generally, to a specific field of application, in this context they are all referred to the kinematic structure of a human figure.

This goal has been achieved implementing a whole-body posture control, based on the position of the centre of mass (CoM). The formulation of the *HuPOSE* algorithm relies on the typical serial robot modelling techniques. The kinematic algorithm has been formulated in terms of a single closed-loop inverse kinematics (CLIK) algorithm relying on an *Augmented Jacobian* matrix. All the reference motion imposed to the control points, including the CoM, are considered as primary task. Such a formulation enables the operator to achieve the motion planning focusing only on the task-related control points, while the algorithm autonomously generate the whole-body posture.

The digital humanoid proposed in this paper is deliberately simpler than others; in fact it has just 39 degree of freedom (DoF)s, because the idea is to build a model which is simple to control while providing good results in terms of simulation. The proposed algorithm, in spite of the simplicity of the kinematic structure of the digital humanoid, allows performing quite complex tasks by forcing physical constraints and some optimization criteria.

In this thesis, particular attention has been paid to the biomechanics of lifting [23], as it is among the main causes of injuries. In fact, it has been estimated that low-back pain is common in the general population: lifetime prevalence has been estimated at nearly 70% for industrialized countries. Studies of workers' compensation data have suggested that low-back pain represents a significant portion of morbidity in working populations [24, 25].

Load-lifting activity can be defined as moving or bringing something from a lower level to a higher one, or vice versa. The concept encompasses stresses resulting from work done in transferring objects from one plane to another, as well as forceful movements. Movement of objects in other ways, such as pulling, pushing, or other efforts are included as well. Some criteria include in the definition the number of lifts per day or average amount of weight lifted.

A great deal of research has been conducted in order to provide information regarding the relationship between low-back disorder and load-lifting activity, providing guidelines to prevent low-back injuries [26]. For instance, the case-control study [27] examined the relationship between back pain and occupational exposures in auto assembly workers, while the prospective study [28] considered the back complaints in 411 employees of four electronics manufacturing plants. Furthermore, studies [29, 30, 31] have demonstrated that back disorder rates vary substantially by industry, occupation, and by job within given industries or facilities.

Biomechanical analysis plays a key role in determining the limits for the load handling activity. In order to avoid muscle fatigue in the lumbar extensor (*erector spinae*) muscle group Tichauer [32] proposed to use the load moment about the lumbosacral disc L5/S1 as the basis for setting the limit for lifting and carrying loads of various sizes.

The *HuPOSE* model is suitable for static biomechanical assessments. In fact the static biomechanical analysis require to compute the static torque at the joints of a human figure. The formulation of the IK algorithm in terms of a single CLIK, using a single *Augmented Jacobian* matrix, suggests the possibility of computing such torques by means of kineto-static duality (KSD). A biomechanical analysis has been conducted using the *HuPOSE* algorithm, in reference to the *cantilever low back model of lifting* proposed in [1], in order to compute the effort acting on lumbosacral diss L5/S1. The results are in good agreement with literature data.

The ever growing availability of computer-aided engineering tools has made possible to speed-up the whole design process. In fact it is possible to build digital mock-ups capable of simulating complex system in full details, so that the construction of a physical prototype is required only at the latest stages of the design process. On the other hand, computer-aided ergonomic tools enable to correctly simulate human beings in digital environment. The possibility to correctly predict human-product and human-process interaction by means of these computer-aided tools, suggests the possibility to train an operator, in order to perform a certain task, within a digital simulation environment. Such a *computer-assisted training* environment will enable the operator to be trained even before a physical mock-up is available, even relying on virtual reality (VR) technologies (virtual training).

Since *HuPOSE* is capable of predicting the correct posture for a human figure, as well as evaluate it from a biomechanical point of view, in reference to a planned task, it is also possible to train the operator in order to perform such a task taking the correct posture.

The industrial world has been increasingly adopting computer-aided solutions in order to design for maintainability and maintenance training tasks, aiming at reducing development costs and to shorten time, improving product and service quality. In fact, when technical systems are not optimized for future maintenance operations, even simple replacement intervention may be very time consuming, increasing the costs. For these reasons, maintainability is considered an added value and a competitive factor [33]. Although the design for maintainability [34] has a positive effect on the operational costs that the user will face using the system, it may increase the purchase price. However, the overall life cycle cost [35] will be certainly lower.

Computer-based training systems created to simulate machine assembly maintenance are normally operated by means of ordinary human-computer interfaces (keyboard, mouse, etc), but this usually results in systems that are far from the real procedures, and therefore not effective in terms of training. A better solution may come from the combination of virtual reality techniques and haptic interaction. Carrying out simulations of maintenance activities within a virtual environment gives to a person the ability to directly interact with 3D virtual models for maintenance purposes. Engineers can employ it to evaluate aspects of human-centric design for maintainability (accessibility, reachability, tool usability, part mount/dismount ability). With respect to well-established techniques based on digital humanoids, the first-person approach offers a more direct, intuitive control over the interaction activity, thus speeding up the maintenance checks, along with the opportunity to find out better design solutions from the maintainability point of view. Furthermore, maintenance operators (mechanics, technicians) can be trained within a highly interactive, realistic virtual reality simulator, thus combining advantages of a safe training environment with the value of the "learning by doing".

ViRstperson[36] is a virtual reality software system developed at the *Italian Center for Aerospace Research* (CIRA) - Virtual Reality Laboratory for carrying out digital maintenance simulations based on a first-person approach. It is aimed at supporting engineering and technical activities such as design-time maintenance procedure validation and maintenance training. Techniques employed for improving the realism of the interactive experience include advanced lighting and shadowing to improve the user's spatial awareness within the virtual environment and a complete dynamics simulation facility which rules the interaction of all bodies within the environment, including sensor-attached anthropomorphic parts (e.g. a digital glove) [37, 38, 39, 40].

Training is one of the most rapidly expanding areas of application of VR technologies, with virtual training being developed in industry, commerce, the military, medical and other areas of education and in a variety of types of rehabilitation. Virtual reality systems represent a powerful tool for training humans to perform tasks which are otherwise expensive or dangerous to duplicate in the real world. The idea is to provide a digital simulation environment in which an operator can be trained to perform a task by directly interacting with the digital environment, using appropriate devices, even before a physical system is available. For example, flight simulators have been used for decades to train pilots for both commercial and military aviation. These systems have advanced to a point that they are integral to both the design and the operation of modern aircraft. VR systems are also making headway into training for manned space operations. In 1993, NASA used an immersive virtual environment to train flight team members for a Hubble Space Telescope repair mission [41]. They concluded the virtual training system had a beneficial effect on crew performance during flight operations. The U.S. military is aggressively pursuing networked virtual environments for the distributed simulation of integrated combat operations [42]. This technology will allow diverse land, sea, and air elements to train together in complex scenarios involving both real and autonomous agents. The military is also interested in VR systems for maintenance training. The National Guard is investigating a virtual training system for maintenance and trouble shooting tasks on the M1A1 Abrams tank, the M2A2 Bradley fighting vehicle, and the TOW II missile system[43].

All of the above examples of virtual reality training make extensive use of advanced computer graphics. Some of them incorporate audio feedback as well. None provide force cues to the user. When the task to be performed involves the manual manipulation of objects, the need for haptic feedback becomes evident.

In order to increase the level of realism during the execution of manual tasks in VR, the senses of touch and kinesthesia must be addressed. Force feedback is beginning to find its way into virtual reality training systems. In Clover et. al. [44] a PUMA 560 robot was used to simulate the control column forces of a Boeing 777 aircraft. NASA has also taken steps to add haptic information to their virtual reality simulators [45]. The Charlotte™manipulator was used to replicate the feel of massive payloads handled by EVA crew members [46]. Some of the most exciting applications of force feedback are found in surgical simulations. Much of this research has focused on training for minimally invasive procedures [47, 48, 49]. In [50] is presented a VR-based system for industrial training, in [51] is exposed how a fully immersive VR visualization suite, called *Cybersphere*, can be used in conjunction with a collaborative product suite to achieve a training environment for manufacturing industries. In [52] a mixed reality system for simulating gas metal arc welding is presented, aimed at training human welders The system is comprised of a real welding torch attached to a force feedback device, a head-mounted display, a 6 DoFs tracking system for both the torch and the user's head, and external audio speakers. The simulation runs in real-time, using a neural network to determine the quality and shape of the created weld based on the orientation and speed of the welding torch [53, 54, 55]. The welding process and resulting weld bead are displayed in a virtual environment. In [56] a low-cost VR desktop application (*V-REALISM*) for maintenance training of a centrifugal pump system is proposed.

Compared with traditional training approaches, these computer-assisted training systems allow trainees to properly operate new equipments before they are actually installed or available. Perceptual cues and multi-modal feedback (e.g., visual, auditory, and haptic) provided to trainees enable these training systems to more effectively transfer virtual training to real world operation skills. Furthermore, such systems can provide higher degree of freedom for operation and the results of improper operation can be simulated without incurring the associated costs in terms of human injury and equipment repair.

To have better structure and easier implementation, a virtual training system can be modelled as an integrated system consisting of a training task-planning module. instruction module, a simulation module, a performance evaluation model, and an interface module [50].

In all cases such training rests upon the assumption that what is learned in the virtual environment transfers to the equivalent real world task. The issue of determining how well the training in a virtual environment transfer to a manual task in the real world is a fundamental issue common to many virtual training systems.

In [57] an experiment is proposed in order to investigate the benefits of force feedback for virtual reality training for a fairly elementary manual task of construction a LEGO™ biplane model. A virtual mock-up of biplane assembly, incorporating both visual and haptic feedback, provides the training platform. Results show that training with haptic feedback provides a significant performance benefit.

Recently, there has been also much interest in using virtual environments in the training of people with learning disabilities [58, 59, 60], in rehabilitation following brain damage caused by traumatic brain injury [61, 62, 63], stroke [64, 65] and neurodegenerative diseases [66].

In this thesis attention has been focused on load-lifting task training. A computer-assisted training session has been conducted. The basic idea is to provide a simulation environment in which an operator can be trained to perform a planned task taking the correct posture which will be given to the trainee as visual feedback.

Although the *HuPOSE* algorithm described in this thesis, has been initially conceived for DHM applications, developing efficient algorithms aimed at controlling a high-articulated chain, such as a human figures, it has implications in the fields of humanoid robotics as well. In fact the increasing attention of the robotics community towards *humanoid robotics* [67, 68, 69] is not simply related to the ancestral ambition of *building something that looks like a human*, but has also an immediate and objective reason. In particular, it arises from the apparently obvious fact that for all actions performed daily by humans, the objects that they manipulate and the environment where they live have been built or structured “on a human scale”. For instance, all the objects that we manipulate have been conceived based on the shape of our hands.

If we really want to build machines effectively able to cooperate with human beings, we need to design robots that not only can move through environments designed for humans, but can also handle objects particularly suited to our physical structure and our behaviour. For instance, bipedal robots could potentially move in the same space where people work, such as an industrial plant with stairs and handrails specifically designed for human use. In this way, these robots could cooperate with humans and even collaborate with one another using already working ordinary tools or machinery. Further considerations can be made even under the aspect of human-robot and robot-robot communication channels [70]; for instance humanoid robots could even be used in the therapy of some forms of mental disorders [71]. It is therefore necessary to develop efficient models that enable us to accurately control the motion of humanoid robots. On the other hand, it is also necessary to develop simulation tools to study robots behaviour in *unstructured* environments, considering the safety issues arising from the interaction with humans.

Chapter 2

State of the art

Nowadays, a great deal of product design, prototyping, and manufacturing activities rely on the capability of digital human modelling and simulation tools, as they enable the designers to reduce the number of iterations required in order to refine a product/process.These tools are largely used in several industrial activities. For instance, they are suitable for conducting ergonomic assessments in vehicle interior design process activity (Figure 2.1). Indeed vehicle's occupant comfort and safety is nowadays recognized by car manufacturing industry as a key factor to achieve economic success. These are, in fact, the major areas in which manufacturers can distinguish them selves from the competition. This is demonstrated by the emphasis on ergonomics, comfort and safety in today's car brochures, as well as by the increasing attention car magazines devote to ergonomics and safety in test reports.

To ensure adequate comfort and safety levels, it is essential that manufacturers systematically address ergonomics and safety throughout the car design process. Since today a major part of that design process is digital, an accurate representation of the occupant in the digital world is necessary in order to study occupant comfort and safety in 3D CAD. However, human beings come in many shapes and sizes, have many different preferences and can adopt many different postures.

In the field of production process, DHM allows to simulating the human presence in the factory floor during the whole production process (Figure 2.2).

The advantages offered by digital human models over traditional ergonomics methods, such as guidelines, tables, two-dimensional templates or

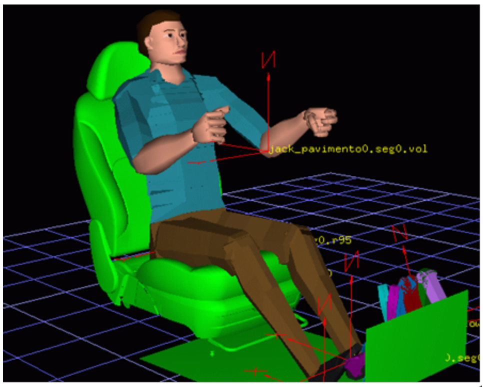


Figure 2.1: Ergonomic evaluation of vehicle interior with JAck™digital human model.

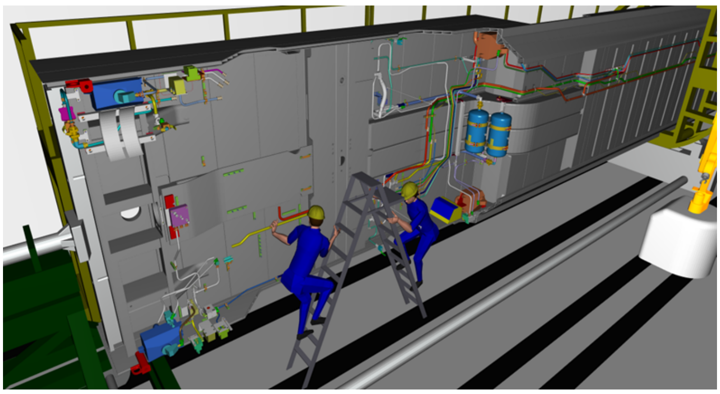


Figure 2.2: Simulation of industrial activity in digital simulation environment.

user clinics, can be summarized as [72]:

- **time-related advantages**: detailed evaluation of designs with user questionnaires, clinics or mock-ups can take weeks or even months. Digital human models, instead, enable designers to conduct user and task simulation using only CAD data. Otherwise, designers must often wait for a mock-up to conduct ergonomic studies and, consequently, this may cause delays to the design process, or, more likely, the design process continues without the benefit of timely ergonomics input;

- **cost-related advantages**: in addition to being time-consuming, the production of mock-ups is an expensive process. The cost of a digital human model software can be less than the costs of making one full size mock-up. Furthermore, digital human models enable ergonomics input to be provided much earlier in the design process, reducing the likelihood of expensive or unfeasible modifications being necessary later on;

- **accuracy-related advantages**: 3D digital human models offer far more accuracy than guidelines, two-dimensional templates or numerical tables. The human body is highly complex and a large variety of combinations and correlations between body dimensions exists. Three-dimensional human models are able to reflect this complexity.

2.1 Digital human models for industrial application.

This section provides a brief overview of the the most common digital human simulation tools currently used in industry

2.1.1 Tecnomatix™ Jack™

Jack™ human simulation system was developed at the *Center for Human Modeling and Simulation* at the University of Pennsylvania in the 1980s & 1990s. It was initially conceived as an ergonomic assessment and virtual human prototyping system for NASA space shuttle development. Later, it also gathered funding from the U.S. Navy and U.S. Army for dismounted soldier simulation, from the U.S. Air Force for maintenance simulation. The software is currently sold as an ergonomic human simulation tool-kit called Tecnomatix™ Jack™ by Siemens. The research and development underlying Jack system have led to such standards as *H-anim*[1] [73, 74] The digital human model Jack™ is based on body dimension measurements taken from the Anthropometric Survey of U.S. Army Personnel [13], it consists of 69 segments, 68 joints, a 17-segment spine, 16-segment hands, coupled shoulder/clavicle joints and 135 DoFs. Figure 1.4 shows the skeleton of Jack™ digital human. It is also possible to impose joint limits to the humanoid's kinematic model derived from NASA studies [13].

The software allows to create various types of humans, choosing from a menu the following predefined human figures:

- Large, medium and small humans, as defined by SAE measurements–based on SAE recommended human physical dimensions (SAE J833).
- Short and tall man and woman-human figure extremes based on the anthropometric data reported in [13].
- Large, medium and small Japanese humans - based on recognized Japanese body size database.
- High resolution man and woman - detailed representations of 50th percentile males and females, as defined by [13]

It is also possible to animate the humanoid using both key-frame and IK methods. Yet, the latter method does not allow to achieve a stable whole body motion of the humanoid, as it manage a limited number of link at time. The software allows to conduct ergonomic analysis by means of *Task Analysis* and *Occupant Packaging Toolkits.*

2.1.2 HUMOSIM

An algorithmic framework, consisting of an interconnected, hierarchical set of posture and motion modules that control aspects of human behaviour, such as gaze or upper-extremity motion, was developed at the *Human Motion Simulation* (HUMOSIM) laboratory at the University of Michigan in

[1] Humanoid Animation (*H-Anim*) is an approved ISO standard, developed in the late '90s, for humanoid modelling and animation in representing humanoids in X3D/VRML. It provides specifications for defining interchangeable human figures so that those characters can be used across a variety of 3D games and simulation environments.

order to provide a different approach to the control of human figure models and the analysis of simulated tasks [75]. Analysis modules, addressing issues such as shoulder stress and balance, are integrated into the framework. The main feature of the framework is a comprehensive system for motion simulation and ergonomic analysis specifically designed to be independent of any particular human modelling system. The modules are developed as lightweight algorithms based on closed-form equations and simple numerical methods that can be communicated in written form and implemented in any computer language. The modules are independent of any particular figure model structure, requiring only basic forward-kinematics control and public-domain numerical algorithms. Key aspects of the module algorithms are "behaviour-based", meaning that the large amount of redundancy in the human kinematic linkage is resolved using empirical models based on laboratory data. The implementation of the HUMOSIM framework in human figure models allows to simulate human interactions with products and workspaces using high-level, task-based control.

2.1.3 Delmia SAFEWORK® Pro™- Human Modeling

SAFEWORK® implements a digital humanoid made of 104 anthropometric ariables, 99 segments and 149 DoFs. It also has fully articulated spine and hand models as well as joints with coupled range of motion. It's *multivariate algorithm* for anthropometry allows the user to create accurate virtual humans from almost anywhere around the world. The *boundary mannequin approach* implemented in SAFEWORK® allows a better accommodation of targeted population. Its further features include: Postural Analysis, Ergonomic Analysis, Force and Comfort Assessment, Task Module, Clothing Module, Animation Module, Collision Detection, Vision, Library concept, direct and inverse kinematics. SAFEWORK® is capable of evaluate many elements of human performance, from static posture analysis through to complex task activities. It implements a range of tools and methods that specifically analyse how a digital humanoid will interact with objects in the virtual environment. The NIOSH [76, 77] and Snook and Ciriello equations [78] measure the effects of lifting/lowering, pushing/pulling and carrying in order to fully optimize task performance. After inputting an initial and final task posture, a designer can determine a number of task variables such as Action Limit, Recommended Weight Limit, and Maximum

Lifting/Lowering Weight. It integrates a vision module, derived from the NASA 3000 guidelines, containing a vision behaviour model to imitate the realistic movement of the human vision so that "the operator can see what the digital humanoid sees". Four types of vision simulation are provided: binocular, ambinocular, monocular left and monocular right (stereoscopic viewing with depth perception is available in the VR module). The Postural Analysis module allows users to analyse several aspects of human posture. Whole body and localized postures can be examined, scored and iterated to determine operator comfort and performance in accordance with any established comfort database.

2.1.4 RAMSIS™

RAMSIS™ (*Rechnergestütztes Anthropmetrisches Mathematisches System zur Insassensimulation*)[2] is a computer-aided ergonomics and occupant packaging tool developed by German car industry. Its goal was to overcome the limitations of two-dimensional human templates, as well as to provide methods for predicting driver postures and comfort. The core of RAMSIS is a three-dimensional human model capable of simulating vehicle's occupants with a large variety of body dimensions. Since it was conceived with specific reference to car industry, extensive research was conducted on driver postures and comfort, which resulted in a probability-based posture prediction model. No manipulation of the digital humanoid is required, so that fast, realistic and consistent analysis results are possible. RAMSIS offers a number of other analysis tools, e.g. for vision, reach, force and seat belt studies.

Over the years, new research projects have been conducted in order increase RAMSIS' functions, such as a force-based posture and comfort prediction model, seat belt certification, compatibility with full body laser scanners, simulation of seat-occupant interaction and simulation of vehicle ingress and egress.

The primary function of RAMSIS is to provide designers with an accurate representation of vehicle's occupants, both in terms of anthropometry and posture, so that they can ensure proper accommodation of these occupants from the early stage of the design process. A focus for further development

[2]Translated as *computer-aided anthropometrical mathematical system for occupant simulation*

of RAMSIS will be on cognitive ergonomics. Indeed, in today's vehicles, a large amount of information is presented to the driver. An increasing number of devices (e.g. board computers, navigation systems, car phones) and of operating elements all require the driver's attention. At the same time, the influx of information from outside the vehicle increases too, due to intensified traffic, more complex road situations and an many traffic signals. The way in which all this information are managed is of great importance in order to achieve driver comfort and safety.

2.1.5 SANTOS™

The virtual human Santos™ was developed by the Virtual Soldier Research (VSR) Program at The University of Iowa. The early virtual human environment was called Mira™. This 15-DoFs upper-body model with posture and motion prediction was funded by John Deere Inc. and US Army TACOM Automotive Research Center. In 2003 US Army TACOM began funding VSR to develop a new generation of virtual humans called Santos composed of 109 DoFs, which was to be another generation of Mira™. Later on, Caterpillar Inc., Honda R&D North Americas, Natick Soldier System Center, and USCAR (GM, Ford, and Chrysler) joined the VSR partnership. The objective was to develop a new generation of digital humans comprising realistic human models including anatomy, biomechanics, physiology, and intelligence in real time, and to test digital mockups of products and systems before they are built, thus reducing the significant costs and time associated with making prototypes. The philosophy is based on optimization approach for empowering these digital humans to perform, un-aided, in a physics-based world. The research thrusts include the following areas: predictive dynamics, modelling of cloth, hand model, intuitive interface, motion capture, muscle and physiology modelling, posture and motion prediction, spine modelling, real-time simulation and VR. Currently, the capabilities of Santos include whole-body posture prediction, inverse kinematics, reach envelope analysis, workspace zone differentiation, muscle force and stress analysis, muscle fatigue prediction, simulation of walking and running, dynamic motion prediction, physiologic assessment, a user-friendly interface, a hand model and grasping capability, clothing modelling, thermo discomfort assessment, muscle wrapping and sliding, whole-body vibration analysis, and collision avoidance.

Chapter 3

Modelling

This chapter addresses the development of both kinematic and biomechanical models underlying the *HuPOSE* algorithm. The kinematic model, described in Section 3.1, is based on the idea of controlling the posture of a highly redundant kinematic structure, such as a human figure, by means of a limited number of task-related control points which can move on its structure. This goal has been achieved using the serial robots modelling techniques [79]. Indeed, the IK problem is formulated in terms of a single CLIK algorithm by means of an *Augmented Jacobian* matrix presented in Section 3.1.3.

In the section 3.2 the biomechanical model is presented. In order to carry on biomechanical analyses of human figures it is necessary to compute the static torques at their joints, hence the idea arose of taking advantage of the KSD. Namely, these static torques are computed using the transpose of the *Augmented Aacobian* matrix, which has been previously determined to compute the IK problem for the whole human figure.

3.1 Kinematic modelling

Considering a serial manipulator and its FK equation, changing the value of its DH parameters results in the kinematics equations of another manipulator, whose end-effector is located before the real one: that is equivalent to move the control point of the kinematic structure. If the DH values are described in a symbolic form, they are such to identify an arbitrary point as a virtual end-effector (VEE) [80] of a smaller manipulator considered for the control. An arbitrary number of such control points can be considered.

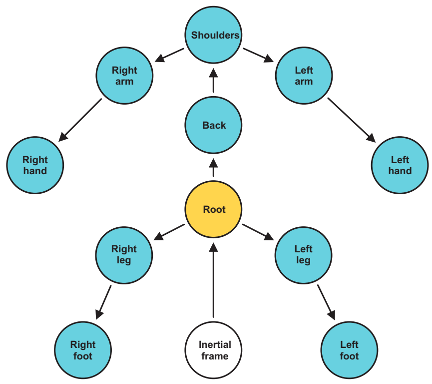


Figure 3.1: Hierarchical model of a human figure.

It is then possible to consider these control points as fixed or moving [81]. Related to a human figure, different kinematic chains will be considered. In addition, during the carrying of a certain task, the postures taken by humanoids largely depend on balancing and mechanics issues, that are only partially related to the considered task. This implies the need for an additional whole-body posture control.

For this purpose, the goal has been to develop an IK algorithm that allows concentrating only on a limited number of task-related control points, without the need of specifying the DoFs of the whole kinematic chain for the posture control. The position of the CoM of the human figure has been taken into account: it is calculated on-line and always kept consistent with the balancing issues of the mechanical structure, by identifying the time-varying CoM as an additional moving control point. It is worth noticing that the relevant control points can be also selected automatically depending on the task and the environment, giving a very powerful tool for simulation.

3.1.1 Hierarchical model of digital humanoid

Firstly, in order to take advantage of the systematic approach typical of serial robots, the human figure has been modelled as the combination of four kinematic chains, which share the same starting point, located at the hip, called *root*.

The resulting model is the hierarchical structure showed in Figure 3.1. Starting from this graph, it is possible to build up the DH model of the whole human figure (figure 3.2).

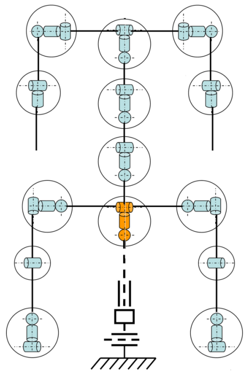


Figure 3.2: DH model of a human figure.

In particular, a FK equation can be defined for each control point, with respect to the *root* reference frame. One or more control points on the provided chains can be selected, by considering the proper set of DH parameters that specify such points. The position and orientation of the *root* node with respect to the reference frame is specified by introducing 6 *virtual joints* (see Section 3.1.2). Thus, the considered kinematic structure has 39 DoFs in all.

This kind of modelling has the advantage of simplicity, but generally it may cause a physical consistency problem, since some links (including the virtual ones) are shared among different kinematic chains. For instance the "back" of the virtual humanoid is shared between its right and left arms. This issue and its solution will be discussed in Section 3.1.5.

3.1.2 Virtual joints

In this section the issue of determining the position and orientation of a human figure with respect to an inertial frame is addressed. For industrial robots identifying such a frame is intuitive, because they have a fixed base. A human figure, instead, is bound to the ground by a one-way constraint, that is the current support plane, for instance one foot.

However, this reference periodically changes during the walk, thus we apparently cannot identify a fixed base starting from which the DH method can be applied (Figure 3.3).

Moreover, the presence of multiple end-effectors (e.g. two hands and two feet) implies the need to describe the position and orientation of several frames, differently from industrial robots, in which the kinematic chain

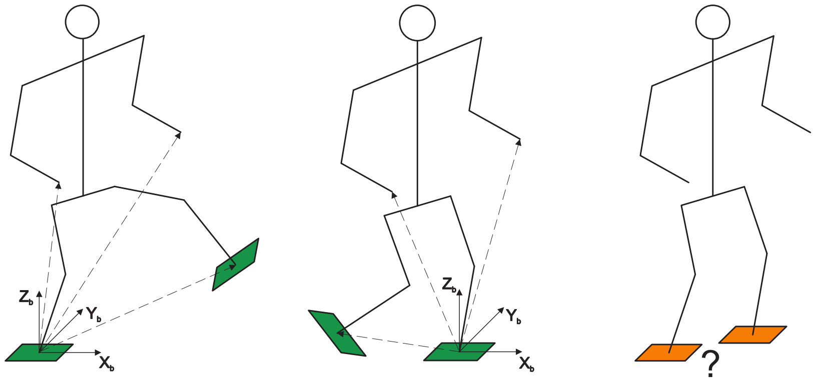


Figure 3.3: Which reference frame?

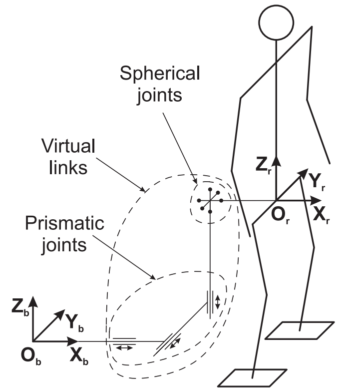


Figure 3.4: Virtual joints approach.

has only one end-effector. This problem has been overcome using the *virtual joints* approach [82]. Namely, a human figure has been conceived as connected to the ground plane through a virtual manipulator consisting of three prismatic and three revolute joints, which characterize its position and orientation. The attaching point has been called *root* (Figure 3.4).

With this approach the humanoid can be considered as a multi legged kinematic chain. Namely, the hands and the feet (and even any other control point) are simply end-effectors that can be controlled with velocity references. In other words, the posture of the human figure is completely specified by the following joint-variable vector:

$$\mathbf{q} = \left[\mathbf{q}_{\mathrm{r}}^{\mathrm{T}} \; \mathrm{q}_1 \; \mathrm{q}_2 \; \ldots \; \mathrm{q}_{\mathrm{n}} \right]^{\mathrm{T}}$$

where $\mathbf{q}_{\mathrm{r}} = \left[\, \mathbf{p}_{\mathrm{r}}^{\mathrm{oT}} \; \boldsymbol{\phi}_{\mathrm{r}}^{\mathrm{oT}} \,\right]^{\mathrm{T}}$ identifies the *root* frame. Moreover, virtual joints technique makes unnecessary the management of closed kinematic chains (e.g. during the phase of double support). Indeed, this condition becomes merely equivalent, from a kinematic point of view, to impose a null velocity reference to the feet.

3.1.3 Augmented Jacobian

Each chain has its own FK function, therefore a Jacobian matrix can be computed for a generic control point of the structure. Generally, considering n control points we can define the following set of equations:

$$\begin{aligned}\mathbf{v}_1 &= \mathbf{J}_1\dot{\mathbf{q}}\\ \mathbf{v}_2 &= \mathbf{J}_2\dot{\mathbf{q}}\\ &\vdots\\ \mathbf{v}_\mathrm{n} &= \mathbf{J}_\mathrm{n}\dot{\mathbf{q}}\end{aligned} \tag{3.1}$$

where the generic element $\mathbf{J}_\mathrm{i}$ is the Jacobian matrix related to a specific control point i. It is understood that, if the generic joint variable q_j does not affect $\mathbf{v}_\mathrm{i}$, it is $(\mathbf{J}_\mathrm{i})_\mathrm{j} = \mathbf{0}$. This set of equations can be summarized as

$$\mathbf{v} = \mathbf{J}_\mathrm{AU}\dot{\mathbf{q}} \tag{3.2}$$

where $\mathbf{J}_\mathrm{AU}$ is the so-called *Augmented Jacobian*. On one hand, this approach allows to solve the inverse kinematic problem with only one CLIK algorithm [70, 83]. On the other hand, the trajectories defined for the control points will be all treated as *primary tasks*, unlike other solution methods do, such as null-space based approaches[84, 85].

In particular, in order to define the structure of $\mathbf{J}_\mathrm{AU}$, the vector $\dot{\mathbf{q}}$ must be properly sorted. Since the human figures is composed by four kinematic chains, we can write four different vectors of unknowns:

$$\begin{array}{lclr}\dot{\mathbf{q}}_1 &=& \begin{bmatrix}\dot{\mathbf{q}}_\mathrm{r}^\mathrm{T} & \dot{\mathbf{q}}_\mathrm{rl}^\mathrm{T}\end{bmatrix}^\mathrm{T} & \textit{right leg}\\ \dot{\mathbf{q}}_2 &=& \begin{bmatrix}\dot{\mathbf{q}}_\mathrm{r}^\mathrm{T} & \dot{\mathbf{q}}_\mathrm{ll}^\mathrm{T}\end{bmatrix}^\mathrm{T} & \textit{left leg}\\ \dot{\mathbf{q}}_3 &=& \begin{bmatrix}\dot{\mathbf{q}}_\mathrm{r}^\mathrm{T} & \dot{\mathbf{q}}_\mathrm{b}^\mathrm{T} & \dot{\mathbf{q}}_\mathrm{ra}^\mathrm{T}\end{bmatrix}^\mathrm{T} & \textit{right arm}\\ \dot{\mathbf{q}}_4 &=& \begin{bmatrix}\dot{\mathbf{q}}_\mathrm{r}^\mathrm{T} & \dot{\mathbf{q}}_\mathrm{b}^\mathrm{T} & \dot{\mathbf{q}}_\mathrm{la}^\mathrm{T}\end{bmatrix}^\mathrm{T} & \textit{left arm}\end{array}$$

where $\dot{\mathbf{q}}_\mathrm{r}$ are the velocities of the virtual joints that are shared among four kinematic chains. These vectors can be summarized in only one vector of unknowns

$$\begin{aligned}\dot{\mathbf{q}} &= \left[\begin{array}{cccccc}\dot{\mathbf{q}}_{\mathrm{r}}^{\mathrm{T}} & \dot{\mathbf{q}}_{\mathrm{rl}}^{\mathrm{T}} & \dot{\mathbf{q}}_{\mathrm{ll}}^{\mathrm{T}} & \dot{\mathbf{q}}_{\mathrm{b}}^{\mathrm{T}} & \dot{\mathbf{q}}_{\mathrm{ra}}^{\mathrm{T}} & \dot{\mathbf{q}}_{\mathrm{la}}^{\mathrm{T}}\end{array}\right]^{\mathrm{T}} \\ &= \left[\begin{array}{cccc}\dot{\mathrm{q}}_1 & \dot{\mathrm{q}}_2 & \dots & \dot{\mathrm{q}}_{39}\end{array}\right]^{\mathrm{T}}\end{aligned} \tag{3.3}$$

With this choice, the Augmented Jacobian takes on the following form

$$\mathbf{J}_{\mathrm{AU}} = \begin{bmatrix} \mathbf{J}_{\mathrm{r}} & \mathbf{J}_{\mathrm{rl}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{J}_{\mathrm{r}} & \mathbf{0} & \mathbf{J}_{\mathrm{ll}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{J}_{\mathrm{r}} & \mathbf{0} & \mathbf{0} & \mathbf{J}_{\mathrm{b}} & \mathbf{J}_{\mathrm{ra}} & \mathbf{0} \\ \mathbf{J}_{\mathrm{r}} & \mathbf{0} & \mathbf{0} & \mathbf{J}_{\mathrm{b}} & \mathbf{0} & \mathbf{J}_{\mathrm{la}} \end{bmatrix} \tag{3.4}$$

The matrix $\mathbf{J}_{\mathrm{AU}}$, with the proposed humanoid model, has 39 columns, while the number of its rows depends on the number of control points considered (in this case 4).

3.1.4 Center-of-Mass Jacobian

Unlike industrial manipulators and, more generally, non-ambulatory robots, humanoids must concern about their balance while performing any task. If this does not happen, obviously, the humanoid would lean over and fall. Moreover, humanoids are inherently hyper-redundant, having a much higher number of joints than traditional industrial robots. Consequently, there are many postures that achieve the same position for its body terminals, corresponding to control points. Also, taking into account the balancing issues allows the humanoid to attain more natural posture, similar to those of human beings.

For this, the VEEs technique[80] has been implemented also with respect to the CoM of the digital humanoid, which becomes a further control point for the kinematic chain. In particular, the trajectory of the CoM can be defined in such a way that its vertical projection on the current support plane (namely, the centre of pressure (CoP)) belongs to the stability polygon formed by the feet (Figure 3.5). It is worth noticing that the constraint about the CoP will be treated as a primary task, as well as the other tasks.

The basic idea is to obtain a differential relationship like

$$\mathbf{v}_{\mathrm{G}} = \mathbf{J}_{\mathrm{G}}\dot{\mathbf{q}} \tag{3.5}$$

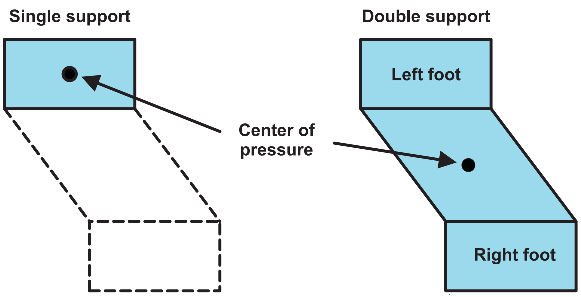


Figure 3.5: Center of Pressure and support plane.

where $\mathbf{J}_\mathrm{G}$ is a $3 \times n$ matrix, called *Center-of-Mass Jacobian.* Then, Equation (3.5) will be inserted in Equation (3.1) as a further control point. For this purpose, we can define the CoM of a kinematic chain composed of n links as

$$\mathbf{p}_\mathrm{G} = \frac{\sum_{i=1}^{n} m_i \, \mathbf{p}_{\mathrm{G_i}}}{\sum_{i=1}^{n} m_i} = \frac{1}{m} \sum_{i=1}^{n} m_i \, \mathbf{p}_{\mathrm{G_i}} \tag{3.6}$$

Equation (3.6) can be derived with respect to time

$$\mathbf{v}_\mathrm{G} = \frac{1}{m} \sum_{i=1}^{n} m_i \, \mathbf{v}_{\mathrm{G_i}} \tag{3.7}$$

Since the CoM of each link can be considered as a VEE, it is always possible to write the differential relationship

$$\mathbf{v}_{\mathrm{G_i}} = \mathbf{J}_{\mathrm{G_i}} \dot{\mathbf{q}}$$

where

$$\mathbf{J}_{\mathbf{G_i}} = \begin{bmatrix} \gamma_{x,1} & \dots & \gamma_{x,i} & 0 & \dots & 0 \\ \gamma_{y,1} & \dots & \gamma_{y,i} & 0 & \dots & 0 \\ \gamma_{z,1} & \dots & \gamma_{z,i} & 0 & \dots & 0 \end{bmatrix}. \tag{3.8}$$

Indeed, if the vector $\dot{\mathbf{q}}$ has been properly sorted, $\mathbf{v}_{\mathrm{G_i}}$ can be affected at most by the first i links of the chain. Now, Equation (3.7) can be written as

$$\mathbf{v}_\mathrm{G} = \frac{1}{m} \left(\sum_{i=1}^{n} m_i \, \mathbf{J}_{\mathrm{G_i}} \right) \dot{\mathbf{q}} \tag{3.9}$$

By comparing Equations (3.5) and (3.9), we can finally assume

$$\mathbf{J}_\mathrm{G} = \frac{1}{m} \sum_{i=1}^{n} m_i \mathbf{J}_{\mathrm{G_i}} \tag{3.10}$$

Given $\mathbf{J}_{\mathrm{G}}$, the CoM's velocity $\mathbf{v}_{\mathrm{G}}$ becomes a further control point for the kinematic chain. Thus, we can insert the kinematic relation (3.5) in the equations set (3.1). As a result, we will have an Augmented Jacobian matrix with two more rows, that are related to the components of $\mathbf{v}_{\mathrm{G}}$ projected on the current support plane. As mentioned above, the implemented inversion algorithm assures that a constraint on CoM velocity becomes a high-priority task to be achieved, without using null-space projection.

Finally, as it will be shown in Section 3.2, it is worth emphasizing that the formulation of the kinematic problem in terms of a single *Augmented Jacobian* matrix $\mathbf{J}_{\mathrm{AU}}$ suggests also the possibility to use the KSD [83] to compute the joint torques due to forces applied to kinematic structure of the humanoid. In particular, the definition of the CoM jacobian $\mathbf{J}_{\mathrm{G}}$ suggests the possibility to use the KSD to compute the balancing torques due to the weight of the kinematic structure of the humanoid robot.

3.1.5 Conflicting tasks

As mentioned above, some tracts of the humanoid structure are shared among apparently different kinematics chains. For instance, the right and left arms of the humanoid share a common tract, namely the back and the virtual links. But, if actually the left and right arms were modelled as *independent* chains, they could perform different or even conflicting tasks. For this, IK algorithms for multi-legged robots generally provide two different solutions for the left and right arm. In particular, for the back it will be

$$\dot{\mathbf{q}}_{\mathrm{bl}} \neq \dot{\mathbf{q}}_{\mathrm{br}} \tag{3.11}$$

where $\dot{\mathbf{q}}_{\mathrm{br}}$ and $\dot{\mathbf{q}}_{\mathrm{bl}}$ are different solutions obtained considering the back belonging respectively to the right and to the left arm. However, this issue is commonly solved with the following choice for the joint velocity vector of the back:

$$\dot{\mathbf{q}}_{\mathrm{b}} = \frac{1}{2}\left(\dot{\mathbf{q}}_{\mathrm{bl}} + \dot{\mathbf{q}}_{\mathrm{br}}\right) \tag{3.12}$$

This guarantees a physical consistent solution, but in general none of the conflicting tasks will be actually achieved. A further criterion has been developed in order to manage the occurrence of conflicting task which, as far as it is known, it is not available in literature. The proposed solution takes into account the manipulability of each kinematic chain. Namely, each solution is weighted with the reciprocal of its manipulability measure (Equation 3.13). This weighted average of different IK solutions, in this case $\dot{\mathbf{q}}_{\mathrm{br}}$ and $\dot{\mathbf{q}}_{\mathrm{bl}}$, is such that as the manipulability of a chain decreases, e.g. m_{br} the related solution $\dot{\mathbf{q}}_{\mathrm{br}}$ becomes predominant. It is worth to emphasize that the proposed approach include the Equation 3.12 when $m_{bl} = m_{br}$.

$$\dot{\mathbf{q}}_{\mathrm{b}} = \frac{\frac{1}{m_{bl}}\dot{\mathbf{q}}_{\mathrm{bl}} + \frac{1}{m_{br}}\dot{\mathbf{q}}_{\mathrm{br}}}{\frac{1}{m_{bl}} + \frac{1}{m_{br}}} = \frac{m_{br}\dot{\mathbf{q}}_{\mathrm{bl}} + m_{bl}\dot{\mathbf{q}}_{\mathrm{br}}}{m_{br} + m_{bl}} \tag{3.13}$$

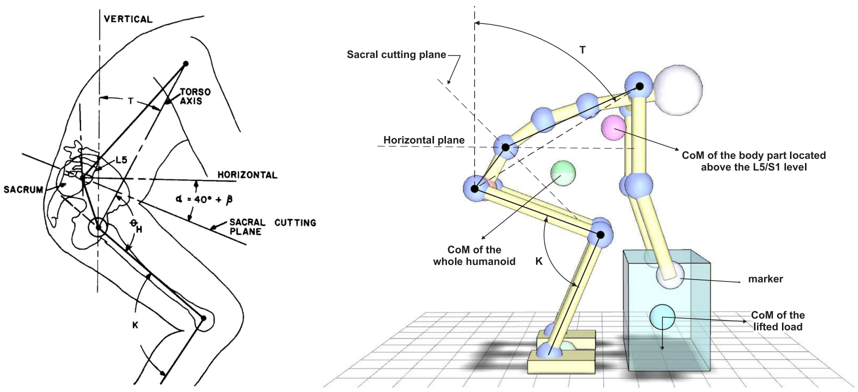
The CLIK algorithm based on the Augmented Jacobian cleverly resolves also this issue. Indeed, the vector of solution $\dot{\mathbf{q}}$ has been sorted in such a way that its elements appear just once, thus the inversion algorithm provides only one solution that is consistent with all the physical constraints. On the other hand, the main problem related to the application of the Augmented Jacobian method is the matrix inversion, due to its dimensions ($\mathbf{J}_{\mathrm{AU}}$ has 39 columns) and consequently to the detection of its singularities.

3.2 Biomechanical modelling

The formulation of the IK problem in terms of a single CLIK algorithm, using a single Augmented Jacobian matrix, suggests also the possibility to compute the static torques at joints of a human figure, due to forces applied at any points of the kinematic structure, by means of KSD [83]. The main feature of *HuPOSE* model is its suitability to implement multiple-point kinematic control for a human figure using a single CLIK algorithm [79], (something like the serial robots), through the Augmented jacobian matrix $\mathbf{J}_{\mathrm{AU}}$. Thus, if a generalized vector of forces $\mathbf{f}_{\mathrm{i}}$ is applied at a generic point $\mathbf{p}_{\mathrm{i}}$ of the kinematic structure, the related torque joints $\boldsymbol{\tau}_{\mathrm{i}}$ will be:

$$\boldsymbol{\tau}_{\mathrm{i}} = \mathbf{J}_{\mathrm{i}}^{\mathrm{T}}\mathbf{f}_{\mathrm{i}} \tag{3.14}$$

where$\mathbf{J}_{\mathrm{i}}$ is its Jacobian matrix. The *cantilever low-back* biomechanical model of lifting illustrated in [1], showed in Figure 3.6(a), has been considered as reference, while Figure 3.6(b) shows the same model applied to the *HuPOSE* human figure.



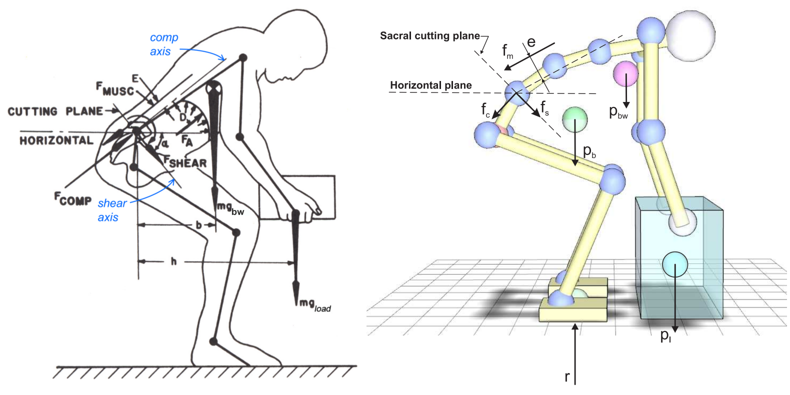
(a) (b)

Figure 3.6: Cantilever low-back biomechanical model as proposed by Chaffin et al. [1] (a) applied to *HuPOSE* human figure (b).

3.2.1 Validation of the biomechanical model

The dynamic biomechanical model of load-lifting described in [1] showed that the moment at the hip can become quite large, especially when the load is lifted far from the body. In order to avoid muscle fatigue in the lumbar extensor (erector spinae) muscle group, Tichauer [32] proposed to use the load moment about the lumbosacral disc L5/S1 as the basis for setting the limit for lifting and carrying loads of various sizes. From a biomechanical point of view, the fact that large moments are created at lumbar spine when heavy loads are lifted raises the question on the nature of the internal forces necessary to stabilize the spine while incurring such load moments.

A simple static model of the lumbar spine during the load-lifting was proposed by Morris et al. [86], in which it was assumed that two kind of internal forces are involved in order to balance the external load moment. One is produced by the extensor erector spinae muscles, which exert their action at an average distance E form the lumbosacral disc L5/S1 of approximately $5cm$ posterior to the centre of rotation in the spinal discs; the second, due to the abdominal pressure, acts on the diaphragm [87]. This model showed also that, while the load is lifted, a large compression force raises in the spinal column that acts to compress the discs. The existence of this compression was also confirmed experimentally. In-vivo measurements in [88], and later in [89, 90], were conducted in order to determine experimentally its amount.



(a) (b)

Figure 3.7: Planar static analysis using the cantilever low-back biomechanical model as proposed by Chaffin et al. [1] (a) conducted using *HuPOSE* human figure (b).

A simple static analysis proposed in [1], which does not take into account the abdominal pressure, can be conducted first by identifying the relevant forces involved, showed in Figure 3.7(a), where $\mathbf{p}_\mathrm{l}$ is the load due to the lifted weight, $\mathbf{p}_\mathrm{b}$ is the weight of the whole human figure, $\mathbf{p}_\mathrm{ub}$ is the weight of the body part located above the L5/S1 level, $\mathbf{r}$ is the reaction of the plan, $\mathbf{f}_\mathrm{m}$ is the force produced by the erector spinae muscles, $\mathbf{f}_\mathrm{c}$ and $\mathbf{f}_\mathrm{s}$ are, respectively, the compression and the shear force acting on the lumbosacral disc L5/S1. In particular $\mathbf{p}_\mathrm{l}$, $\mathbf{p}_\mathrm{b}$, $\mathbf{p}_\mathrm{ub}$ and $\mathbf{r}$ are external forces while $\mathbf{f}_\mathrm{m}$ $\mathbf{f}_\mathrm{c}$ and $\mathbf{f}_\mathrm{s}$ are internal forces. The analysis of the forces acting on the L5/S1 disc begins with the computation of the moments. If

$$\sum_i \mathbf{m}_\mathrm{i} \tag{3.15}$$

is the sum of the external moments about the L5/S1 disc due to the load lifted and to the weight of the humanoid, applying the equilibrium of moments, an internal moment $\boldsymbol{\tau}_\mathrm{L5/S1}$ at L5/S1 level must arise, such that

$$\boldsymbol{\tau}_\mathrm{L5/S1} = \sum_i \mathbf{m}_\mathrm{i} \tag{3.16}$$

The torque $\boldsymbol{\tau}_\mathrm{L5/S1}$ is due to the force $\mathbf{f}_\mathrm{m}$ and can be computed as

$$\mathbf{f}_\mathrm{m}\mathrm{E} = \boldsymbol{\tau}_\mathrm{L5/S1} \tag{3.17}$$

Posture:	(cm)	h = 30	b = 20	E = 6.5
	(°)	T = 60	K = 120	Θ = 110
Loads:	(N)	$\mathbf{p}_{\mathrm{bw}} = -350$	$\mathbf{p}_{\mathrm{l}} = -450$	

Table 3.1: Posture and loads used for the load-lifting analysis.

The second member of the Equation (3.16) is computed using the KSD. Once the average moment arm E between the erector spine muscles and the lumbosacral disc L5/S1, is determined (approximately 5 cm), it is possible to compute the muscular effort $\mathbf{f}_{\mathrm{m}}$ from the Equation 3.17.

For the compression $\mathbf{f}_{\mathrm{c}}$ and shear $\mathbf{f}_{\mathrm{s}}$ forces it is enough to project the relevant forces along the directions perpendicular and parallel to the sacral cutting plane. Than, the shear and compression forces can be calculated through the static equilibrium equations

$$\mathbf{p}_{\mathrm{bw}} \cos\alpha + \mathbf{p}_{\mathrm{l}} \cos\alpha + \mathbf{f}_{\mathrm{m}} + \mathbf{f}_{\mathrm{c}} = 0 \tag{3.18}$$

$$\mathbf{p}_{\mathrm{bw}} \sin\alpha + \mathbf{p}_{\mathrm{l}} \sin\alpha - \mathbf{f}_{\mathrm{s}} = 0 \tag{3.19}$$

With reference to the load-lifting task showed in Figure 3.7(a) the efforts $\mathbf{f}_m$, $\mathbf{f}_c$ and $\mathbf{f}_s$, have been computed using the *HuPOSE* model (Figure 3.7(b)) and, then, compared with the results of the low-back biomechanical model proposed in [1].

	$\mathbf{f}_{\mathrm{m}}$ (N)	$\mathbf{f}_{\mathrm{c}}$ (N)	$\mathbf{f}_{\mathrm{s}}$ (N)
Literature:	−3154	−3612	−656
Simulation:	−3220	−3560	−660

Table 3.2: Lifting analysis: simulation results compared to the literature data [1]

The results proposed in the published literature are referred to a single posture of the human figure identified by torso (T) and knee (K) angles showed in Figures 3.6(a) and 3.6(b) and reported in Table 3.1: As showed in Table 3.2, *HuPOSE* algorithm produces results that are in good agreement with the published literature data, at least for the posture considered.

Chapter 4

HuPOSE model implementation

HuPOSE algorithm has been validated with the simulation of typical human activities. The results have shown that it considerably speed-up the posturing of human figures. Indeed, the posture control enables the operator to focus on the task planning only for the relevant control points. The algorithm generates autonomously the whole body posture, taking into account primary tasks, such as, for instance, the position of the CoP[1].

Moreover, it is possible to include multiple objective functions in the algorithm in order to further optimize the posture of the human figure (e.g. joint maximum strength, displacement from a neutral position). Since the weighted pseudo-inverse technique has been used, it is also possible to "tune" the kinematic behaviour of the humanoid *by hand*, changing the coefficients of the weighting matrix accordingly.

4.1 Simulations in Virtual Reality

In this section several VR simulations are presented. First of all, on the basis of the typical hierarchical approach exposed in Section 3.1.1, a geometric model of a human figure has been built up, resulting in a VRML model used for the simulations (Figure 4.1).

After that, the *HuPOSE* model has been implemented with *MathWorks MATLAB – Simulink*™ software. Since a weighted pseudo-inverse has been

[1]The CoP is forced within the support polygon.

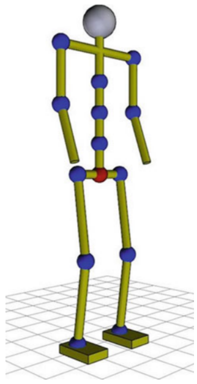


Figure 4.1: VRML model of the human figure.

adopted to compute the inverse kinematics, a proper choice of weights and of some optimization criteria have granted quite natural and fluid movements for the digital humanoid, in spite of both the limited number of control points and the high degree of redundancy of its kinematic structure. As a result, despite the simplicity of planning the movements of the digital humanoid, it is possible to simulate quite complex tasks, by planning the trajectory only for the task-related control points. The virtual humanoid can walk or even climb a ladder, as will be shown in the following sections.

4.1.1 Standing-up from a sitting position.

In Figure 4.2 different screen shot of a standing-up simulation are showed. This task has been achieved just by imposing a null velocity to the feet of the digital humanoid and by giving a velocity reference to its pelvis. As a further constraint, the *balance control* is active, forcing the CoP within the support plane (Section 3.1.4). As showed, the digital humanoid performs the assigned movement always keeping itself in balance. Furthermore, the constraint on the CoP's position results in quite natural movements.

In a similar way, it is possible to simulate the sitting down from a standing position.

4.1.2 Collision avoidance

The approach proposed can be used to take into account also possible obstacles in the humanoid workspace.

Figure 4.3 shows again a standing up simulation, but this time there is

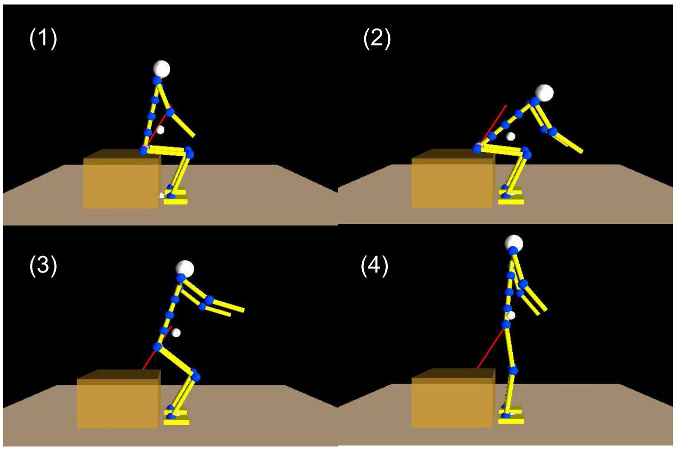


Figure 4.2: Standing up from a sitting position.

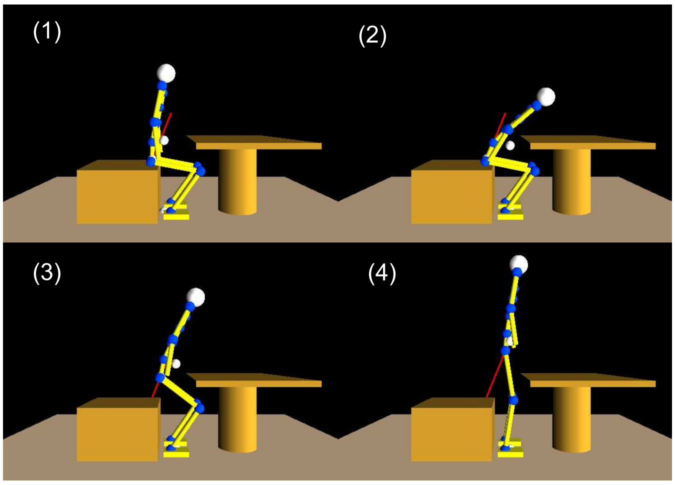


Figure 4.3: Standing up from sitting position near a table.

a table. This task has been achieved by assigning to the relevant control points velocity references coming from repulsive potential fields [91], while the planning has been done similarly to the previous case (Section 4.1.1).

4.1.3 Reaching an object on a table.

Figure 4.4 shows the humanoid reaching an object on a table. Similarly to the previous simulations, this task has been achieved by giving, again, a null velocity reference to feet of the digital humanoid and a reference motion to its hand. The whole body motion is generated autonomously by *HuPOSE* algorithm. It is worth to highlight the simplicity of the task planning, which is required only for the relevant control points, in this case just one hand, with no need to concern about the posture generation, as it is managed by the inversion *HuPOSE* algorithm itself.

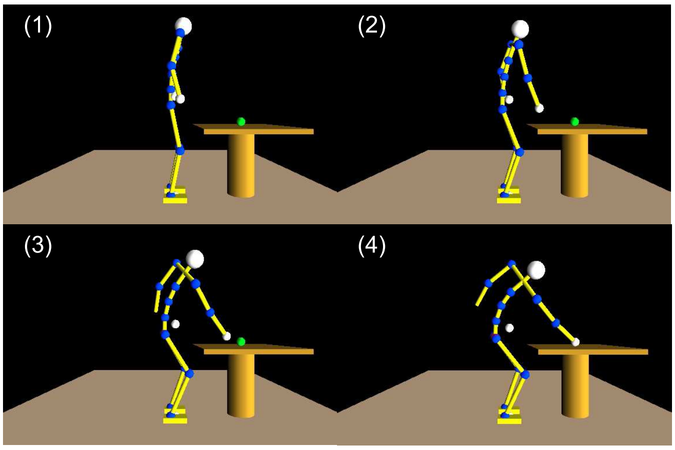


Figure 4.4: Reaching an object on a table.

4.1.4 Reaching an object on the ground.

In order to emphasize the *HuPOSE* algorithm's capability of generating whole-body motion, even specifying the reference motion only for one control point in Figure 4.5 is shown a task of reaching an object located on the ground. It is worth to highlight that the humanoid takes very natural postures, even though no dynamic model has been implemented.

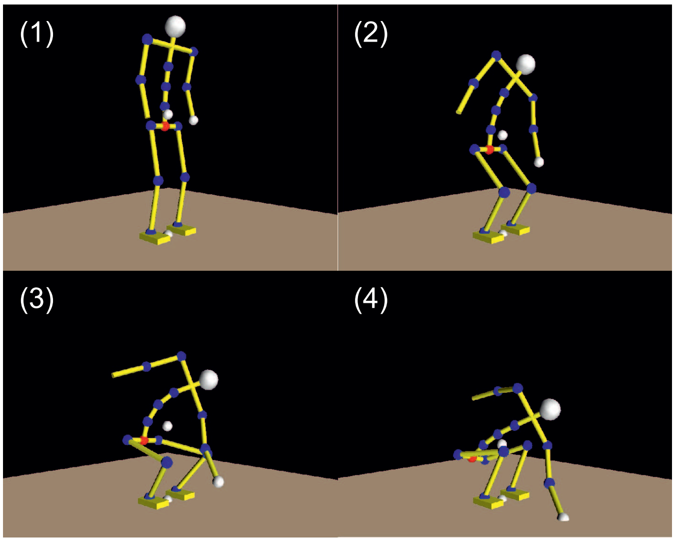


Figure 4.5: Reaching an object on the ground

4.1.5 Load-lifting tasks

In this section the results of the simulation of quite complex tasks are reported. The CLIK algorithm has always taken into account the constraints about the CoP's position, as mentioned above. The results obtained are quite interesting in both digital human simulation and robotics field, mainly because of the ease of the motion generation. Figure 4.6 shows the simulation of load-lifting task. Even in this simulation, the task planning involve only the task-related control points, imposing a null reference to the feet of the humanoid and a reference motion to its hands. The algorithm is also capable of taking into account the variation of the CoM of the mechanical system due to the load lifted and change the posture of the humanoid accordingly[2]. This issue is even more evident in the simulation shoved in Figure 4.7.

Figure 4.7 shows the humanoid lifting a load and releasing it on a table. This simulation has been planned similarly as the previous one. The simulation proposed highlights the ease of the task planning, focusing on the relevant control points, as well as the power of the *HuPOSE* algorithm in autonomously generating the whole-body posture.

[2]In such a way that the CoP of the whole system still belongs to the support polygon

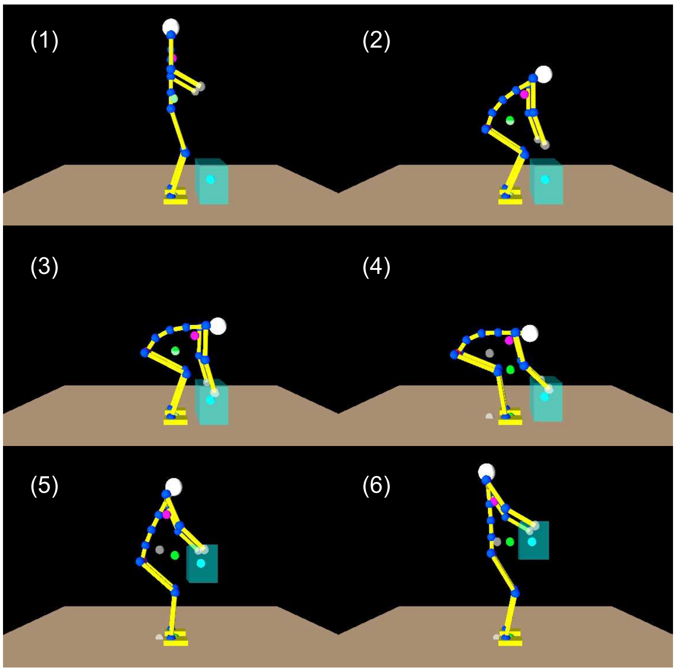


Figure 4.6: The humanoid lifts a load.

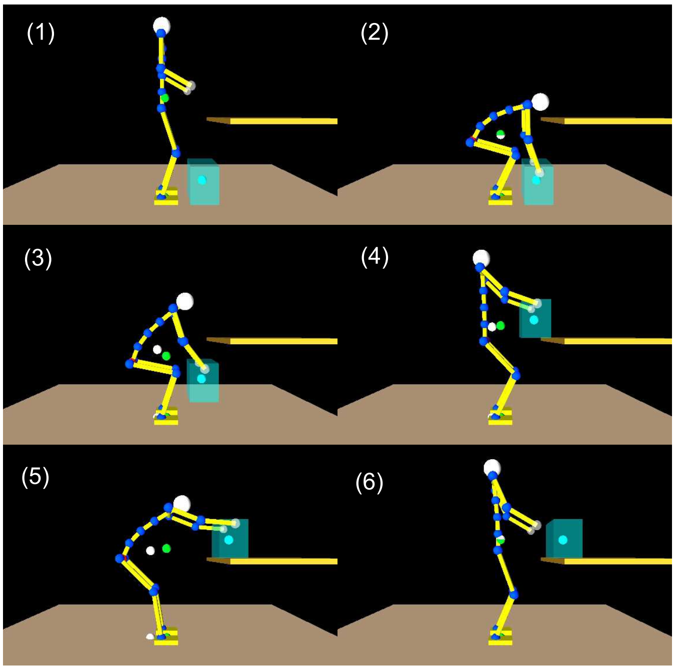


Figure 4.7: The humanoid lifts a load and releases it on a table.

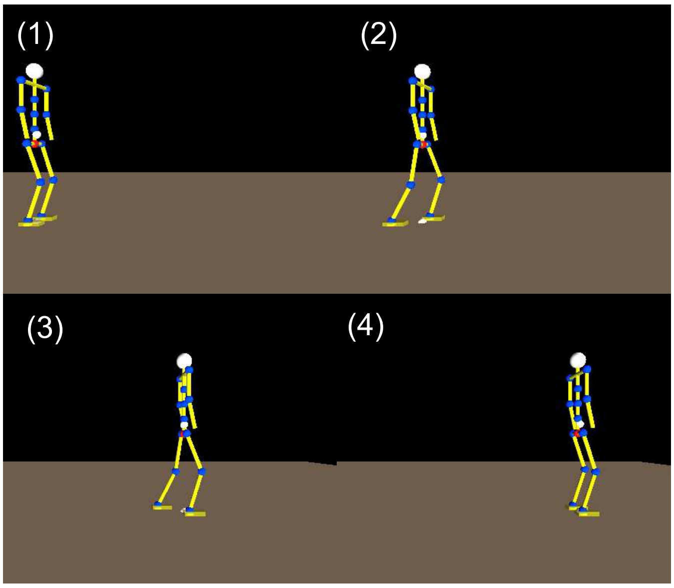


Figure 4.8: The humanoid walking.

4.1.6 Bipedal locomotion

In this section the simulation of walking for a human figure is presented (Figure 4.8). Again, in spite of the complexity of the task, the motion planning is very simple. This task has been achieved by imposing a motion reference to the feet of the humanoid, while the CoP is forced to belong to the support polygon. The support polygon periodically changes during the walk, thus the motion reference for the CoP will change accordingly. Even for this simulation the resulting motion is quite natural.

Even simulating a humanoid climbing a ladder (Figure 4.9) is quite simple. It can be planned similarly to the previous task and the resulting motion is still quite natural.

4.1.7 Different kinematic behaviours

The *HuPOSE* model is also capable of generating different kinematic behaviours in reference to the same planned task. Figure 4.10 shows the humanoid taking different postures in reference to a load-lifting task.

Since a weighted pseudo-inverse has been adopted to compute the inverse kinematics, different postures can be generated by means of a proper choice of weights and of some optimization criteria. Anyway it is possible to

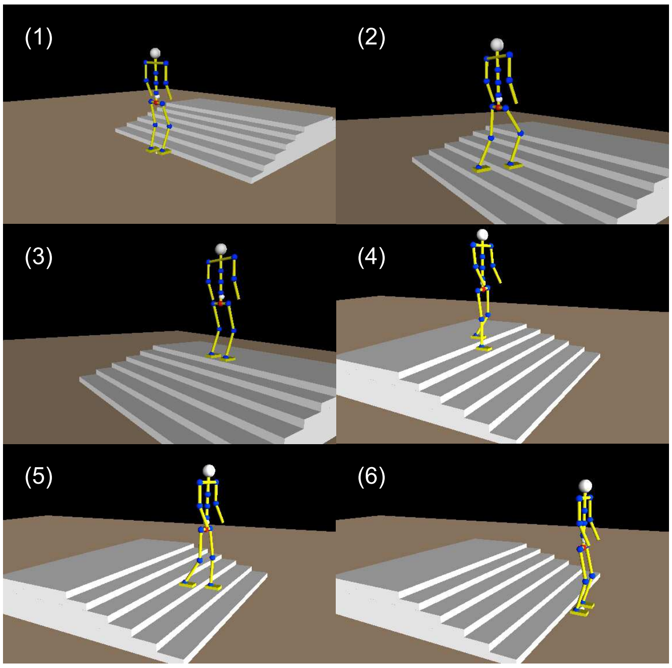


Figure 4.9: The humanoid climbing a ladder.

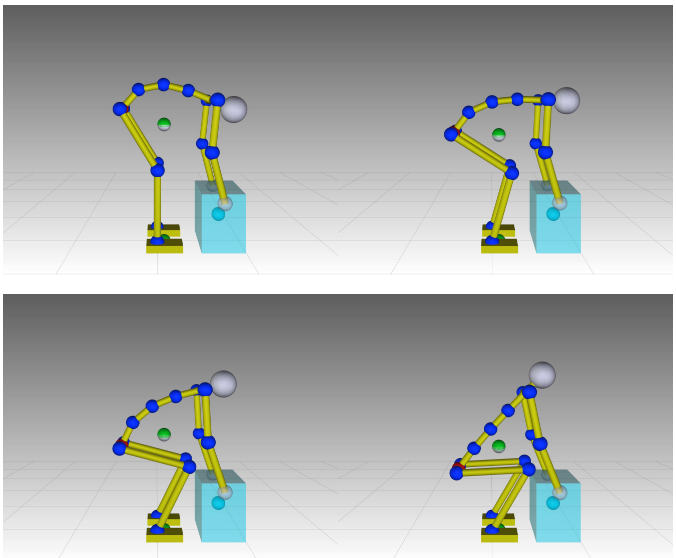


Figure 4.10: Different kinematic behaviours.

implement further constraint (e.g. joint maximum strength, displacement from a neutral position).

4.2 Motion capture

Although most of the DHM software currently available are suitable for MOCAP applications, they require the tracking of many markers in to animate their digital human models. Morever, optical MOCAP systems generally require the operator to wear a specific suit for the tracking. Since these commercial software are closed source, it is not possible to know the algorithms implemented, nor to modify them. Consequently, the operators are bound to the use specifications provided by the software manufacturers.

On the other hand, the *HuPOSE* algorithm is capable of generating human-like postures for human figures, controlling their whole-body motion by means of a limited number of task-related control points (even one). Thus, it is also suitable for MOCAP applications by means of a limited number of markers. From this point of view the *HuPOSE* algorithm represents quite an innovation in this field. As it will be discussed in the Section 4.3, the motion generation of *HuPOSE* digital humanoid occurs offline because, currently, the *HuPOSE* algorithm is implemented in *Matlab–Simulink*™.

It is worth emphasize that the aim of the presented work is not to provide a standalone DHM application. Indeed, several simulation software providing digital human models much more complex then *HuPOSE* are already available. The intent is, instead, to simplify the MOCAP process for the commercial DHM software available.

Considering that *HuPOSE* model does not require a minimum number of markers to be tracked, together with the limitation of the available DHM application, the idea arose of using the *HuPOSE* model as a filter (Figure 4.11), placed between the tracking system and the commercial digital humans application to be animated. Namely, the trajectory of the relevant markers tracked by the MOCAP system are used as input for *HuPOSE* model, relying on it for the posture generation. Later, the relevant reference motion required by a specific digital human model to be animated are generated by the *HuPOSE* algorithm itself.

In this way the *HuPOSE* algorithm computes the kinematic inversion, taking as input the control points' position tracked by the MOCAP system

Figure 4.11: *HuPOSE* used as filter between MOCAP system and DHM application.

and provides to a DHM application all the further motion reference needed to animate its digital humans. This allows also to achieve whole-body posturing for commercials digital humans. Moreover, since *HuPOSE* algorithm is able to generate the correct posture for a human figures in reference to a certain task, it is also possible to generate correct posture for a proprietary digital human model.

Briefly, it is than possible to achieve a whole-body posture generation also for proprietary DHM applications, such as Jack™, by means of a limited numbers of task-related control points, relying on *HuPOSE* filter, which allows to completely bypass the proprietary kinematic algorithms.

4.3 Computer-assisted training

In this section is presented a procedure to conduct a computer-assisted training session. The aim is to provide a simulation environment, in which an operator can be trained to perform a planned task, taking the correct posture. The basic idea is to track only the control points which are strictly relevant to the task to be accomplished by means of markers worn by the operator during the execution of the task (e.g. in reference to the load-lifting task showed in Figure 4.6 the MOCAP system tracks only the operator's hands). The *HuPOSE* model determines autonomously the correct posture to be taken by the operator, taking into account several criteria (e.g. joint maximum strength, joint range of motion, low-back analysis). Finally, the determined posture will be provided to the operator as feedback.

It is worth noticing that, although most of the modern DHM software tools are able to perform assessments such as, for instance, low-back biomechanical analysis, to the best of author's knowledge, none of them is suitable for such an application. From this point of view, this idea represent quite a new approach to the ergonomic evaluation of the manual load handling.

A virtual training session has been conducted at *IDEAinVR Lab* of University of Naples Federico II, in reference to a load-lifting task. The MOCAP

Figure 4.12: Motion capture setup at *IDEAinVR Lab*

laboratory set-up consists of six infrared (IR) OptiTrack™cameras V100:R2 with a frame rate of up to 100 frames per second (FPS) positioned as showed in Figure 4.12 and controlled by the software ARENA™. The MOCAP system tracks the markers and provide the motion reference to *HuPOSE* humanoid in order to generate the correct posture. Later, the *HuPOSE* algorithm generates the further motion reference required to animate the digital human Jack™(see Section 4.2).

The IR cameras track the markers within the capture volume. Namely, at each frame the camera system acquire a point cloud from within the capture volume and provide it to the ARENA™software, which is capable of "recognising" the markers among the various frames in order to reconstruct their path, as well as their trajectory. Generally this procedure occurs on-line in order to track the markers in real time. Since the *HuPOSE* algorithm is implemented in *Matlab–Simulink*™, the posture generation occurs offline. Thus the generation of the motion reference for the markers runs off-line as well. Namely, while the IR cameras system track the markers, ARENA™determines, and stores, their trajectory. Once the tracking is done, ARENA™generates a file containing the motion reference to be used in the *HuPOSE* model.

An operator, wearing two passive markers[3] at his wrists performs the load-lifting task intentionally taking an incorrect posture (Figure 4.15(a)).

Once the camera system has tracked and recorded the position of the

[3]A passive marker is coated with a retro reflective material to reflect IR signals generated near the cameras lens. Active markers instead, rather than reflecting light back that is generated externally, are themselves powered to emit their own light.

markers, a C3D[4] [92] file is generated, containing their motion reference, by the software ARENA™. Than, the positions of the tracked markers are extracted from the C3D file in Matlab–Simulink™ using the BTK [93] and used off-line as motion reference for the *HuPOSE* humanoid model, which generates the correct posture in reference to the planned task. Finally, the *HuPOSE* filter generates the further motion reference required to animate Jack™'s digital human (Figure 4.13).

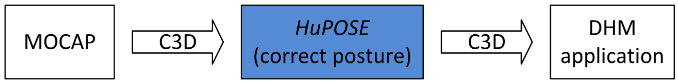


Figure 4.13: Block diagram of the computer-assisted training procedure.

A schematic representation of the conducted computer-assisted training session is represented in Figure 4.14.

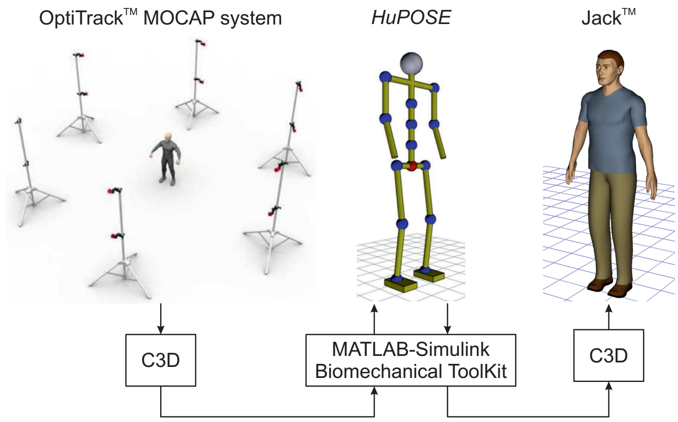
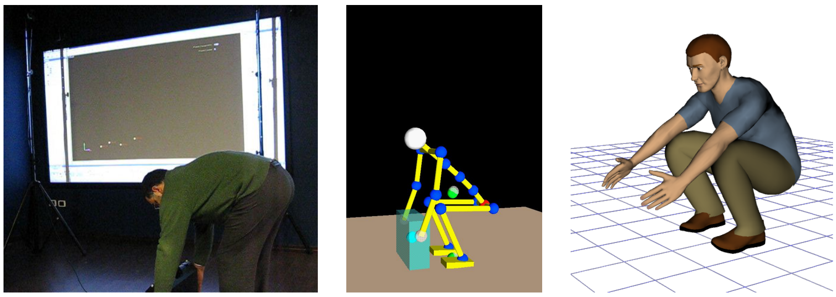


Figure 4.14: The MOCAP system tracks the markers position and generates a C3D file for the BTK, *HuPOSE* filter then generates the motion reference for Jack™ virtual human on the basis of the markers position tracked by the MOCAP system.

Figure 4.15 shows screen shots of the computer-assisted training session conducted. The operator wearing two markers at his wrists performs the load-lifting task taking incorrect posture Figure 4.15(a). Using the motion

[4] C3D standard exchange file format has been chosen because of its portability. In fact it can be imported, as well as generated, by most of the modern MOCAP software. Furthermore, it can be easily manipulated in Matlab–Simulink™ by means of several available toolbox.



(a) (b) (c)

Figure 4.15: Operator lifting a load takes incorrect posture intentionally (a), *HuPOSE* humanoid takes the correct posture using the motion reference provided by the operator (b), Jack™ takes the correct postures using the motion reference generated by *HuPOSE* filter.

reference acquired by the MOCAP system the *HuPOSE* model generates the correct posture in reference to the task performed by the operator Figure 4.15(b). Finally, *HuPOSE* model provide all the further motion reference needed to achieve the motion Jack™ human model (Figure 4.15(c)).

In conclusion, using the proposed approach,it is possible to animate a commercial digital human model, such as Jack™, by means of two markers using a MOCAP system. The animation relies on *HuPOSE* model, which in this case acts as a filter, allowing to bypass the proprietary kinematic algorithms underlying the commercial DHM application. This is a quite new approach to this fields. However, it is still possible to perform all the analyses that the commercial DHM software provide, e.g. ergonomic evaluation of postures using NIOSH or RULA indexes. For instance, it would be possible to conduct an ergonomic evaluation of the posture determined by *HuPOSE* using a DHM application, such as Jack™.

In such a way it is possible to take advantage of the *HuPOSE* model capability for the posture generation without the need of develop a standalone application. Furthermore, it is possible to validate the postures that *HuPOSE* generates using a software tool, such as Jack™, which is considered a de facto standard in the field of product and process design.

Chapter 5

Conclusions and future work

In this chapter a brief overview of the methods presented in this thesis and the achieved results will be discussed. Proposals for future research will be discussed as well

5.1 Main results

The main contribution of the developed *HuPOSE* model, is in the computation of an *Augmented Jacobian* matrix to specify trajectories for different control points, including the control of the CoM of the kinematic structure. The IK problem has been solved using a single CLIK algorithm. The motion reference imposed to the control points, including the CoM, have all the same priority and will be all treated as a primary task, unlike other solution methods do, such as null-space based approach.

The definition of the CoM's position as a primary task, has granted quite natural movements to the human figure, acting as a whole-body posture kinematic control, in spite of the limited number of considered control points. Moreover, these control points can move on specified sections of the humanoid, giving the possibility of controlling nominally every point on the kinematic structure. Motion reference coming from repulsive potential field can be imposed to the control points in order to achieve obstacle avoidance.

The proposed approach cleverly solve also the conflicting task in which the human figure may occur while performing a planned task. In fact each element of the joint velocity vector appears just once in the kinematic equation, thus the inversion algorithm provides only one solution that is consistent with all the physical constraints.

Finally, although the described model is advanced in terms of quality of analysis, it is also computationally efficient. Specifically, a symbolic representation for the kinematics of the digital humanoid has been derived. In this way, it is possible to change in real-time several characteristic parameters of the chain, such as the applied loads, without further computational overload.

Moreover, the symbolic implementation leads to a very fast response of *HuPOSE* algorithm with respect to complex simulations in the humanoid configuration space. Moreover, the *HuPOSE* model lends itself to a very different set of applications. For example, it makes it possible to achieve whole body motion, and than to observe the resulting joint motions, simply by planning the trajectory of a limited number of control points.

HuPOSE can be used for animation of digital humans in the field of ergonomics and process analysis. In fact, despite the complexity and cost of already existing software tools dedicated to this type of analysis, generally their simulation algorithms are still tied to "key-frame[1]" animation techniques.

Since *HuPOSE* is capable of performing whole-body motion for human figures by means of a limited number of task-related control points, it is also suitable for MOCAP application using a limited number of markers. Indeed, *HuPOSE* has been used together with a MOCAP system in order to conduct a computer-assisted training session in reference to a load-lifting task. The MOCAP system tracks only the task-related control points while the *HuPOSE* algorithm generates the whole body motion. Namely, an operator, wearing two markers on his wrists, performs the load-lifting task intentionally taking an incorrect posture. The OptiTrack™MOCAP system tracks the markers' position and provide it as motion reference to *HuPOSE* digital humanoid. Since the *HuPOSE* model is implemented in Matlab–Simulink™the motion generation occurs off-line. The MOCAP software ARENA™generates a C3D file containing the motion reference. Finally, *HuPOSE* humanoid generates the correct posture to be taken by the operator. The correct posture is than showed on a display, so that it is provided as visual feedback to the operator.

[1]Generally DHM software, e.g. Jack™and Human Builder™, implement a procedural animation module Even though it allows to plan complex simulations, e.g. walking along paths, it is not sufficient to simulate more complex tasks such as manipulating objects in presence of obstacles

The aim of *HuPOSE* is not to provide a standalone digital human simulation environment. Indeed, such applications are already available on the market (e.g. Tecnomatix™Jack™, RAMSIS™, Human Builder™) which provide more complex digital human models than *HuPOSE* . Moreover, these software are so widely used in the companies as to be currently considered a *de facto* standard in the filed of the product/process design. Yet, the animation process of their digital humanoids is very time demanding, as it still relies on key frame techniques. The so called *process simulation* may require hours, or even days, of work to be achieved. Since these are closed source software it is not possible to know the kinematic algorithm implemented, nor to modify them. Hence the operator is bound to the use specification provided by the software manufacturers. Moreover, each proprietary MOCAP software implements its own digital humanoid which require a specific suit, equipped wit tens of markers, to be animated. *HuPOSE* , instead, enables to generate whole body motion for human figure tracking only the relevant control points. Once the motion for the *HuPOSE* human figure is generated, it can provide, as output, the motion of nominally every point of its kinematic structure. Thus, the idea arose of using *HuPOSE* in order to achieve the whole body motion for the proprietary digital human tools. Namely, the whole body motion for *HuPOSE* human figure is generated tracking only the task related control points. Than *HuPOSE* provide the motion reference to all the further points required by the proprietary digital human application to be animated.

In conclusion, *HuPOSE* has been used as a filter between the MOCAP system and DHM application, allowing to generate a whole-body posture for a proprietary digital human model, with the remarkable result of completely bypassing the proprietary kinematic algorithm. The proposed approach has been validated using Tecnomatix™Jack™human model.

A biomechanical simulation has been conducted using the *cantilever low-back biomechanical model* proposed by Chaffin [1]. The analysis considers the human figure as a linkage and determines the efforts acting on the lumbosacral disc L5/S1, by means of static equilibrium equations, for a single posture of the human figure. The same analysis has been conducted using *HuPOSE* [2]. The consistency of biomechanical simulation results provided

[2] In order to conduct the biomechanical analysis, the anthropometry of the *HuPOSE* humanoid has been adapted to that assumed in literature [1]

by *HuPOSE* with literature data raises the interest in a deeper investigation about the biomechanical parameters related to the computation of the efforts in a human being from a static analysis. In this scenario the *HuPOSE* algorithm gives a very powerful and easy to use tool even for biomechanical and ergonomic analyses.

Moreover, since *HuPOSE* is capable of performing animation of a human figures, it also allows to plot the efforts on the lumbosacral disc L5/S1 due to a load lifting for the whole duration of the task.

Moreover, further objective function can be developed in order to optimize the posture prediction for the digital humanoid.

5.2 Proposal for the future

Currently the *HuPOSE* algorithm is implemented in MATLAB–Simulink™, this is the reason the motion generation occurs off-line. In the near future the model can be implemented in a different environment in order to achieve real time motion generation. An immediate feasible step further could certainly be the development of a desktop-oriented application also using a pointing device such as a mouse to control the digital humanoid. The possibility of achieving whole body motion even moving a single point of the digital humanoid will considerably speed up the animation process. Even such a "simple" step further will be a considerable innovation. In fact, as widely exposed, current digital human simulation tools still rely on key-frame techniques, making the process simulation considerably time demanding.

Once a real time application is developed *HuPOSE* could also be interfaced with a tracking system to generate the real time animation, similarly to the training session presented in Section 4.3. Even though the MOCAP application by means of a limited number markers is quite an innovation it is not still appealing for the companies. In fact using a MOCAP system in order to perform digital human animations presents several disadvantages. Firstly, they are generally expansive compared to desktop solutions. Since a MOCAP system requires to be calibrated before it is used, it need to be installed in a dedicated lab. Moreover, skilled operator are required to use such a system. All this aspects result in costs companies are unwilling to sustain, even though this kind of simulation are strongly required.

A further disadvantage is certainly related to the fact that, in order to achieve the animation by means of a MOCAP system, the operator is required to "actually" perform the task within the capture volume. Namely, the operator is required to imitate the movements that a real operator performs during the execution of the task. For example, in reference the load-lifting task, the operator has to move within the capture volume in accordance with the movements that a real operator will do (e.g. walking, lifting, standing-up and so forth). Such a procedure may results tiring.

The possibility to conduct the animation of digital humans on a desktop environment, using low cost tracking devices such as, for instance, Microsoft Kinect™, resulted particularly appealing, for the companies. Such a procedure will define smarter ways to capture and analyse human movements in manufacturing procedures. Indeed, recently SIEMENS has developed a plug-in for Tecnomatix™ Jack™ digital human model, capable of capture human motion using Microsoft KINECT™. This application simplify motion capture for ergonomics analysis. Yet, it still requires the operator to imitate the movements to be performed by the digital human. Thus, in order to perform the task simulation, the operator has to move as if he/she was actually performing the task. This results in a repetitive, as well as tiring, activity, similarly to conducting the process simulation using a MOCAP system. This is due to the kinematic model underlying Jack™ digital human, which does not implement a whole-body motion control.

Since *HuPOSE* is capable of generating autonomously the whole body posture of human figure by means of a limited number of control points, a smarter solution would be to provide the reference motion to the task-related control points using a low cost device such as Microsoft KINECT™, tracking, for instance, the operator's hand. Such a procedure would enable the operator to animate the digital humanoid from his/her desk moving only the hands, with no need to "actually" perform the task.

In order to train the companies' personnel, a well-established procedure is to provide training videos. This method is particularly used in manufacturing companies in order to train their personnel to properly perform assembly/disassembly procedure on complex systems. These videos basically provide animations showing a step-by-step procedures to be followed in order to properly perform the task. Such animations are realized starting from a digital mock-up of the assembly. Since the execution of assembly/disassembly procedures involve human operators, it would be very useful, in order to achieve a higher level of training, to create training videos showing the digital humanoids performing the assembly/disassembly task in order to provide, for instance, the correct posture to be taken by the operators. The amount of time required to achieve the animation of digital humans, using the customary key-frame techniques, is the main obstacle to the creation of such videos. Moreover, even though such animations are performed, the quality of the final results strongly depends on the operator's skills as no posture control is implemented. Thus, possible incorrect posture generate accidentally by the operator will be recorded and than showed to the trainee, resulting in incorrect training procedure. A MOCAP systems, would certainly allow to speed up the animation process, but it requires the operator "actually" to perform the task. Namely, the operator must imitate the movement to be executed during the real task. Yet, even in this case, no control of posture is implemented. Namely, as the operator moves in the capture volume, in order to simulate the task execution, the digital humanoid implemented in the MOCAP software will "simply" reproduce the movements of the operator. So that, if the the operator takes incorrect postures they will be recorded, and than showed to the trainee, resulting in incorrect training procedure. *HuPOSE* cleverly solve this issue. Indeed, since it is capable of generating whole-body posture it requires to track only the relevant control points. It will generate the correct posture for the human figure independently of the posture assumed by the operator in the capture volume. From this point of view, *HuPOSE* acquire the motion reference *filtering* the operator's movements. Moreover, since *HuPOSE* is able to perform biomechanical analyses, it is also possible to determine if an assigned assembly/disassembly task, given the weight of the components to be manipulated, requires more than one operator in order to be executed correctly .

Since *HuPOSE* is not implemented in VR, the computer-assisted training session proposed in Section 4.3 requires a physical object, and in general a physical mockup, to be conducted. A further development will be to implement *HuPOSE* in a VR environment, in such a way that the trainee will be able to perform a planned task on a digital mockup, using, for instance, a VR headset (*virtual training*) while *HuPOSE* will provide to the trainee, in real time, the correct posture to be taken.

A possible virtual training scenario can be referred to an assembly/disassembly task. The trainee performs the planned task on a digital mock-up while the relevant control points are tracked, e.g. trainee's hands. Than *HuPOSE* provides to the trainee the correct posture in real time, taking into account, for instance, the weight of the parts to be manipulated.

Bibliography

[1] D. B. Chaffin, G. B. J. Andersson, and B. J. Martin, *Occupational Biomechanics, 4th Edition*. Wiley, May 2006.

[2] F. Caputo, G. Di Gironimo, and A. Marzano, "Ergonomic optimization of a manufacturing system work cell in a virtual environment," in *Acta Polytechnica*, vol. 46, pp. 21–27, 2006.

[3] F. Caputo, G. Di Gironimo, and S. Papa, "A virtual reality system for ergonomics and usability validation of equipment controls," in *Anales de Ingegnería Gráfica*, vol. 18, pp. 47–64, 2006.

[4] G. Di Gironimo and S. Patalano, "Re-design of a railway locomotive in virtual environment for ergonomic requirements," *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 2, pp. 47–57, 2008.

[5] R. D. Buurman, "User-centred design of smart products," *Ergonomics*, vol. 40, no. 10, pp. 1159–1169, 1997.

[6] G. Di Gironimo and A. Lanzotti, "Designing in VR," *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 3, pp. 51–53, 2009.

[7] A. Sundin and R. Örtengren, *Digital Human Modeling for CAE Applications*, pp. 1053–1078. John Wiley & Sons, Inc., 2006.

[8] D. B. Chaffin, D. Thompson, C. Nelson, J. D. Ianni, P. A. Punte, and D. Bowman, *Digital human modeling for vehicle and workplace design.* Society of Automotive Engineers Warrendale, PA, 2001.

[9] J. Tersko, "Process planning: Human simulation," *Industry Week*, November 2006.

[10] K. H. E. Kroemer, "Engineering anthropometry," *Ergonomics*, vol. 32, no. 7, pp. 767–784, 1989.

[11] I. Kaleps, C. E. Clauser, J. W. Young, R. F. Chandler, G. F. Zehner, and J. T. McConville, "Investigation into the mass distribution properties of the human body and its segments," *Ergonomics*, vol. 27, no. 12, pp. 1225–1237, 1984. PMID: 6526003.

[12] H. G. Armstrong, "Anthropometry and mass distribution for human analogues," tech. rep., 1988.

[13] N. A. S. Book, *Anthropometric Source Book. Volume II: A Handbook of Anthropometric Data*, 1978.

[14] A. C. Bittner, "A-CADRE: Advanced family of manikins for workstation design," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 44, pp. 774–777, SAGE Publications, 2000.

[15] Eynard, E., Fubini, E., Masali, M., Cerrone, M., Tarzia, A, "Generation of virtual man models representative of different body proportion and application to ergonomic design of vehicles," in *Proceedings of the IEA2000/HFES2000 Congress. Human Factors and Ergonomics Society*, (Santa Monica, CA), 2000.

[16] M. P. Reed and C. A. C. Flannagan, "Anthropometric and postural variability: limitations of the boundary manikin approach," *SAE International Journal of Passenger Cars–Mechanical Systems*, vol. 109, no. 6, pp. 2247–2252, 2000.

[17] H. Factors, E. Society, and H. . Committee, "Guidelines for using anthropometric data in product design," 2004.

[18] K. Jung, H. You, and O. Kwon, "A multivariate evaluation method for representative human model generation methods: Application to grid method," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 52, pp. 1665–1669, SAGE Publications, 2008.

[19] I. Shaikh, U. Jayaram, S. Jayaram, and C. Palmer, "Participatory ergonomics using VR integrated with analysis tools," in *Simulation Conference, 2004. Proceedings of the 2004 Winter*, vol. 2, pp. 1746 – 1754 vol.2, dec. 2004.

[20] P. Meulen and A. Seidl, "Ramsis-the leading CAD tool for ergonomic analysis of vehicles," in *Digital Human Modeling* (V. G. Duffy, ed.), vol. 4561 of *Lecture Notes in Computer Science*, pp. 1008–1017, Springer Berlin Heidelberg, 2007.

[21] N. Moes, "Digital human models: An overview of development and applications in product and workplace design," in *Proceedings of TMCE (Tools and Methods of Competitive Engineering) International Conference, Ancona*, 2010.

[22] N. Burtnyk and M. Wein, "Computer-generated key-frame animation," *Journal of the SMPTE*, vol. 80, no. 3, pp. 149–153, 1971.

[23] E. Tichauer, "Biomechanics of lifting," *Journal of Occupational and Environmental Medicine*, vol. 13, no. 5, p. 269, 1971.

[24] B. S. Webster, S. H. Snook, *et al.*, "The cost of 1989 workers' compensation low back pain claims.," *Spine*, vol. 19, no. 10, p. 1111, 1994.

[25] D. Spengler, S. J. Bigos, N. A. Martin, J. Zeh, L. Fisher, A. Nachemson, *et al.*, "Back injuries in industry: a retrospective study. i. overview and cost analysis.," *Spine*, vol. 11, no. 3, p. 241, 1986.

[26] D. B. Chaffin, "Manual materials handling and the biomechanical basis for prevention of low-back pain in industry–An overview," *American Industrial Hygiene Association Journal*, vol. 48, no. 12, pp. 989–996, 1987. PMID: 2963515.

[27] L. Punnett, L. J. Fine, W. M. Keyserling, G. D. Herrin, and D. B. Chaffin, "Back disorders and nonneutral trunk postures of automobile assembly workers," *Scandinavian journal of work, environment & health*, pp. 337–346, 1991.

[28] D. B. Chaffin and K. S. Park, "A longitudinal study of low-back pain as associated with occupational weight lifting factors," *American Industrial Hygiene Association Journal*, vol. 34, no. 12, pp. 513–525, 1973. PMID: 4272346.

[29] S. J. Bigos, D. Spengler, N. A. Martin, J. Zeh, L. Fisher, A. Nachemson, M. Wang, *et al.*, "Back injuries in industry: a retrospective study. ii. injury factors.," *Spine*, vol. 11, no. 3, p. 246, 1986.

[30] H. Riihimäki, S. Tola, T. Videman, K. Hänninen, *et al.*, "Low-back pain and occupation. a cross-sectional questionnaire study of men in machine operating, dynamic physical work, and sedentary work.," *Spine*, vol. 14, no. 2, p. 204, 1989.

[31] B. Schibye, T. Skov, D. Ekner, J. U. Christiansen, and G. Sjøgaard, "Musculoskeletal symptoms among sewing machine operators," *Scandinavian journal of work, environment & health*, pp. 427–434, 1995.

[32] E. Tichauer, "A pilot study of the biomechanics of lifting in simulated industrial work situations," *Journal of Safety Research*, vol. 3, no. 3, pp. 98–115, 1971.

[33] G. Di Gironimo and P. Leoncini, "Realistic interaction for maintainability tests in virtual reality," in *Proceedings of Virtual Concept*, 2005.

[34] R. VAUGHAN, "Design for maintainability: The innovation process in long term engineering projects," in *Proceedings of the Conference "The Future of Innovation Studies"*, 2001.

[35] J. K. Seger, "Reliability investment and life-cycle cost," *Reliability, IEEE Transactions on*, vol. R-32, no. 3, pp. 259–263, 1983.

[36] A. F. Abate, M. Guida, P. Leoncini, M. Nappi, and S. Ricciardi, "A haptic-based approach to virtual training for aerospace industry," *Journal of Visual Languages & Computing*, vol. 20, no. 5, pp. 318 – 325, 2009. Multimodal Interaction through Haptic Feedback.

[37] J. Liang, C. Shaw, and M. Green, "On temporal-spatial realism in the virtual reality environment," in *Proceedings of the 4th annual ACM symposium on User interface software and technology*, UIST '91, (New York, NY, USA), pp. 19–25, ACM, 1991.

[38] C. Ware and J. Rose, "Rotating virtual objects with real handles," *ACM Trans. Comput.-Hum. Interact.*, vol. 6, pp. 162–180, June 1999.

[39] S. Rezzonico, R. Boulic, Z. Huang, N. M. Thalmann, and D. Thalmann, *Consistent grasping interactions with virtual actors based on the multi-sensor hand model.* Virtual Environments '95, Wien: Springer, 1995.

[40] I. Poupyrev, M. Billinghurst, S. Weghorst, and T. Ichikawa, "The go-go interaction technique: non-linear mapping for direct manipulation in vr," in *Proceedings of the 9th annual ACM symposium on User interface software and technology*, UIST '96, (New York, NY, USA), pp. 79–80, ACM, 1996.

[41] R. Loftin and P. Kenney, "Training the hubble space telescope flight team," *Computer Graphics and Applications, IEEE*, vol. 15, no. 5, pp. 31–37, 1995.

[42] T. Mastaglio and R. Callahan, "A large-scale complex virtual environment for team training," *Computer*, vol. 28, no. 7, pp. 49–56, 1995.

[43] D. M. McLin and J. C. Chung, "Combining virtual reality and multimedia techniques for effective maintenance training," pp. 204–210, 1996.

[44] C. L. Clover, G. Luecke, J. Troy, and W. McNeely, "Dynamic simulation of virtual mechanisms with haptic feedback using industrial robotics equipment," in *Robotics and Automation, 1997. Proceedings., 1997 IEEE International Conference on*, vol. 1, pp. 724–730 vol.1, 1997.

[45] C. Carignan and D. Akin, "Actively controlled mock-ups for eva training in neutral buoyancy," in *Systems, Man, and Cybernetics, 1997. Computational Cybernetics and Simulation., 1997 IEEE International Conference on*, vol. 3, pp. 2369–2374, 1997.

[46] P. L. Swaim, C. J. Thompson, and P. D. Campbell, "The charlotte (tm) intra-vehicular robot," in *Artificial Intelligence, Robotics, and Automation for Space Symposium*, vol. 1, pp. 157–162, 1994.

[47] R. Baumann and R. Clavel, "Haptic interface for virtual reality based minimally invasive surgery simulation," in *Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on*, vol. 1, pp. 381–386 vol.1, 1998.

[48] C. V. Edmond Jr, D. Heskamp, D. Sluis, D. Stredney, D. Sessanna, G. Wiet, R. Yagel, S. Weghorst, P. Oppenheimer, J. Miller, *et al.*, "Ent endoscopic surgical training simulator.," *Studies in health technology and informatics*, vol. 39, p. 518, 1997.

[49] J. Ward, D. Wills, K. Sherman, and A. Mohsen, "The development of an arthroscopic surgical simulator with haptic feedback," *Future Generation Computer Systems*, vol. 14, no. 3 - 4, pp. 243 – 251, 1998. Virtual Reality in Industy and Research.

[50] F. Lin, L. Ye, V. G. Duffy, and C.-J. Su, "Developing virtual environments for industrial training," *Information Sciences*, vol. 140, no. 1 - 2, pp. 153 – 170, 2002. Interactive virtual environments and distance education.

[51] K. J. Fernandes, V. H. Raja, and J. Eyre, "Immersive learning system for manufacturing industries," *Computers in Industry*, vol. 51, no. 1, pp. 31 – 40, 2003.

[52] K. Fast, T. Gifford, and R. Yancey, "Virtual training for welding," in *Mixed and Augmented Reality, 2004. ISMAR 2004. Third IEEE and ACM International Symposium on*, pp. 298–299, Nov.

[53] C. PembrokeStreet, "Neural networks in materials science," *ISIJ international*, vol. 39, no. 10, pp. 966–979, 1999.

[54] K. Andersen, G. Cook, G. Karsai, and K. Ramaswamy, "Artificial neural networks applied to arc welding process modeling and control," *Industry Applications, IEEE Transactions on*, vol. 26, no. 5, pp. 824–830, 1990.

[55] D. Nagesh and G. Datta, "Prediction of weld bead geometry and penetration in shielded metal-arc welding using artificial neural networks," *Journal of Materials Processing Technology*, vol. 123, no. 2, pp. 303 – 312, 2002.

[56] J. Li, L. Khoo, and S. Tor, "Desktop virtual reality for maintenance training: an object oriented prototype system (v-realism)," *Computers in Industry*, vol. 52, no. 2, pp. 109 – 125, 2003.

[57] R. J. Adams, D. Klowden, and B. Hannaford, "Virtual training for a manual assembly task," *Haptics-e*, vol. 2, no. 2, p. 1, 2001.

[58] J. Cromby, P. Standen, J. Newman, and H. Tasker, "Successful transfer to the real world of skills practised in a virtual environment by students

with severe learning difficulties," in *Proc. 1st European Conference on Disability, Virtual Reality, and Associated Technologies*, pp. 8–10, 1996.

[59] D. Stanton, P. Wilson, and N. Foreman, "Using virtual reality environments to aid spatial awareness in disabled children," in *Proceedings of the 1st European Conference on Disability, Virtual Reality and Associated Technologies*, pp. 93–101, 1996.

[60] D. Strickland, "Virtual reality for the treatment of autism," *Studies in Health Technology and Informatics*, pp. 81–86, 1997.

[61] F. D. Rose, "Virtual reality in rehabilitation following traumatic brain injury," in *Proceedings of the European Conference on Disability, Virtual Reality and Associated Technology*, pp. 5–12, 1996.

[62] F. Rose, E. Attree, D. Johnson, *et al.*, "Virtual reality: an assistive technology in neurological rehabilitation.," *Current Opinion in Neurology*, vol. 9, no. 6, p. 461, 1996.

[63] F. D. Rose, B. M. Brooks, and A. A. Rizzo, "Virtual reality in brain damage rehabilitation: review," *CyberPsychology & Behavior*, vol. 8, no. 3, pp. 241–262, 2005.

[64] Y. S. Lam, D. W. Man, S. F. Tam, and P. L. Weiss, "Virtual reality training for stroke rehabilitation," *NeuroRehabilitation*, vol. 21, no. 3, pp. 245–253, 2006.

[65] F. D. Rose, B. M. Brooks, E. A. Attree, D. M. Parslow, A. G. Leadbetter, J. E. McNeil, S. Jayawardena, R. Greenwood, and J. F. Potter, "A preliminary investigation into the use of virtual environments in memory retraining after vascular brain injury: indications for future strategy?," *Disability and Rehabilitation*, vol. 21, no. 12, pp. 548–554, 1999.

[66] F. D. Rose, E. Attree, B. Brooks, and D. Johnson, "Virtual environments in brain damage rehabilitation: a rationale from basic neuroscience," *Studies in Health Technology and Informatics*, pp. 233–242, 1998.

[67] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki, and K. Fujimura, "The intelligent asimo: system overview and integration,"

in *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*, vol. 3, pp. 2478 – 2483 vol.3, 2002.

[68] K. Kaneko, F. Kanehiro, S. Kajita, K. Yokoyama, K. Akachi, T. Kawasaki, S. Ota, and T. Isozumi, "Design of prototype humanoid robotics platform for hrp," in *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*, vol. 3, pp. 2431 – 2436 vol.3, 2002.

[69] H. Iwata and S. Sugano, "Design of human symbiotic robot twendy-one," in *Robotics and Automation, 2009. ICRA '09. IEEE International Conference on*, pp. 580 –586, may 2009.

[70] B. Siciliano and O. Khatib, eds., *Springer Handbook of Robotics*. Springer, 2008.

[71] B. Robins, K. Dautenhahn, T. Boekhorst, and A. Billard, "Robotic assistants in therapy and education of children with autism: can a small humanoid robot help encourage social interaction skills?," *Univers. Access Inf. Soc.*, vol. 4, pp. 105–120, Dec. 2005.

[72] J. Porter, K. Case, M. Freer, and M. Bonney, "Automotive ergonomics. chapter 3. computer-aided ergonomics design of automobiles," *Publication of: Taylor and Francis Ltd*, 1993.

[73] *ISO/IEC 19774:2006.*

[74] *http://h-anim.org/.*

[75] M. P. Reed, J. Faraway, D. B. Chaffin, and B. J. Martin, "The HUMOSIM ergonomics framework: A new approach to digital human simulation for ergonomic analysis," *SAE Technical Paper*, pp. 01–2365, 2006.

[76] T. R. Waters, V. Putz-Anderson, A. Garg, and L. J. Fine, "Revised niosh equation for the design and evaluation of manual lifting tasks," *Ergonomics*, vol. 36, no. 7, pp. 749–776, 1993. PMID: 8339717.

[77] J. R. Potvin, "Use of niosh equation inputs to calculate lumbosacral compression forces," *Ergonomics*, vol. 40, no. 7, pp. 691–707, 1997.

[78] S. H. Snook and V. M. Ciriello, "The design of manual handling tasks: revised tables of maximum acceptable weights and forces," *Ergonomics*, vol. 34, no. 9, pp. 1197–1213, 1991. PMID: 1743178.

[79] A. Santis, G. Gironimo, L. Pelliccia, B. Siciliano, and A. Tarallo, "Multiple-point kinematic control of a humanoid robot," in *Advances in Robot Kinematics: Motion in Man and Machine* (J. Lenarčič and M. M. Stanišić, eds.), pp. 157–168, Springer Netherlands, 2010.

[80] A. De Santis, P. Pierro, and B. Siciliano, "The multiple virtual end-effectors approach for human-robot interaction," in *Advances in Robot Kinematics* (J. Lennarčič and B. Roth, eds.), pp. 133–144, Springer Netherlands, 2006.

[81] A. De Santis and B. Siciliano, "Inverse kinematics of robot manipulators with multiple moving control points," in *Advances in Robot Kinematics: Analysis and Design* (J. Lenarčič and P. Wenger, eds.), pp. 429–438, Springer Netherlands, 2008.

[82] K. Yamane, *Simulating and Generating Motions of Human Figures.* Springer Tracts in Advanced Robotics, Vol. 9, Springer, 2004.

[83] B. Siciliano, L. Sciavicco, L. Villani, and G. Oriolo, *Robotics: Modelling, Planning and Control.* Springer, 2009.

[84] Y. Nakamura, *Advanced Robotics: Redundancy and Optimization.* Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc., 1st ed., 1990.

[85] B. Siciliano and J.-J. Slotine, "A general framework for managing multiple tasks in highly redundant robotic systems," in *Advanced Robotics, 1991. 'Robots in Unstructured Environments', 91 ICAR., Fifth International Conference on*, pp. 1211 –1216 vol.2, june 1991.

[86] J. M. Morris, D. B. Lucas, and B. Bresler, "Role of the trunk in stability of the spine," *The Journal of Bone & Joint Surgery*, vol. 43, no. 3, pp. 327–351, 1961.

[87] D. L. Bartelink, "The role of abdominal pressure in relieving the pressure on the lumbar intervertebral discs," *Journal of Bone & Joint Surgery, British Volume*, vol. 39-B, no. 4, pp. 718–725, 1957.

[88] A. Nachemson, "Intravital dynamic pressure measurements in lumber discs," *Scand J Rehab Med*, vol. 1, pp. 1–40, 1970.

[89] H. J. Wilke, P. Neef, M. Caimi, T. Hoogland, and L. E. Claes, "New in vivo measurements of pressures in the intervertebral disc in daily life," *Spine*, vol. 24, no. 8, pp. 755–762, 1999.

[90] K. Sato, S. Kikuchi, and T. Yonezawa, "In vivo intradiscal pressure measurement in healthy individuals and in patients with ongoing back problems," *Spine*, vol. 24, no. 23, p. 2468, 1999.

[91] A. De Santis, A. Albu-Schaffer, C. Ott, B. Siciliano, and G. Hirzinger, "The skeleton algorithm for self-collision avoidance of a humanoid manipulator," in *Advanced intelligent mechatronics, 2007 IEEE/ASME international conference on*, pp. 1 –6, sept. 2007.

[92] *http://www.c3d.org/*.

[93] *https://code.google.com/p/b-tk/*.