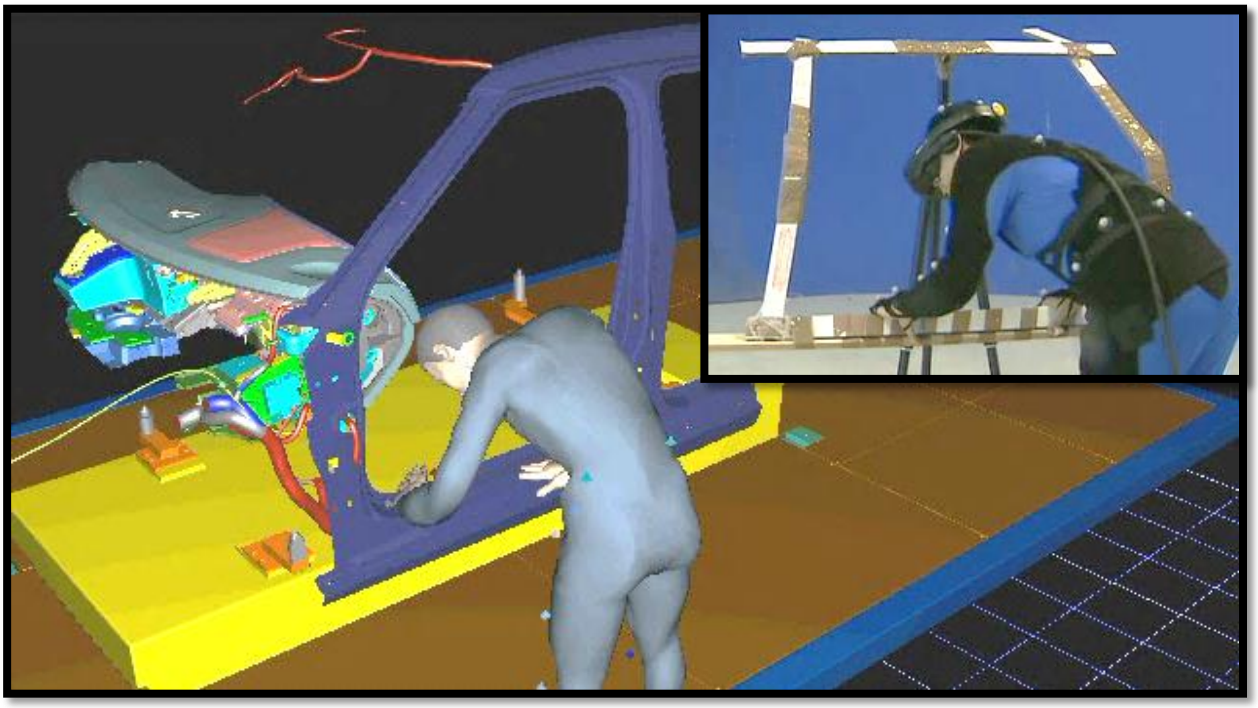

Toward Motion-Capture-Based Digital Human Modelling

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Department of Product and Production Development
Division of Production Systems
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Gothenburg, Sweden 2012

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

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Abstract

Toward Motion-Capture-Based Digital Human Modelling

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Digital Human Models (DHMs) are getting more applicable in the simulation of human postures/actions inside virtual production systems. Despite the existence of various modeling techniques, simulated motions are still looking unrealistic. One way to increase the natural looking of simulated motions is to use real human data as a source for motion simulation algorithms. Motion capture is a common tool to record real human motions and has been widely used in animation and game applications. It is observed that although many research studies embrace the profitability of using real human data for motion simulation in DHM tools, the existing motion capture data can be hardly reused in a systematic way. Number of reasons such as variations in skeleton configurations and motion formats, non-efficient annotating of motions are identified as the reasons for this problem.

In this thesis first a data schema for motion capture data management is presented. The purpose of such schema is to store and manipulate motion data in a way that mentioned problems are not arising. A synthesizer platform is also presented which is able to store motions taken from real human in the database and synthesize new motions using already existing motions. The platform is able to search the database, analyze the data, and feed the data to DHM tools. The platform functionality was tested within two areas: a) by composing new motions by combining the arm motions and walking motions from different subjects and b) by using analysis tools to compare generated motions in a commercial software against captured motions from real human.

Keywords: Digital Human Modeling, Motion Capture Data Management, Virtual Production Tools, Human Motion Simulation

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Gothenburg, 21 April 2012

List of Appended Papers

Paper I	Keyvani, A., Johansson, H., Ericsson, M., Lämkull, D., & Örtengren, R. (2011). *Schema for Motion Capture Data Management*. Paper presented at the Third International Conference on Digital Human Modeling, ICDHM 2011, Held as Part of HCI International 2011, Orlando, USA**.**
Contribution	Keyvani initiated and wrote the paper along with the edit and supervision of other authors. Keyvani was the corresponding author and presented the paper.
Paper II	Keyvani, A., Johansson, H., Ericsson, M. (2012). *Motion Synthesizer Platform for Moving Manikins.* Paper submitted at the second International Conference On Applied Digital Human Modeling, ADHM 2012, Held as Part of AHFE 2012, San Fransisco, USA.
Contribution	Keyvani initiated and wrote the paper along with the edit of other authors. He was the corresponding author and presented the paper.

Other publications:

Keyvani, A., Ericsson, M., Johansson, H. (2011). *A Database Approach to Human Motion Capture Data*. Paper presented at the Swedish Production Symposium, SPS 2011, Lund, Sweden.

Bertilsson, E., Keyvani, A., Högberg, D. and Hanson, L. (2012). *Assessment of manikin motions in IMMA*. Paper submitted to 4th International Conference on Applied Human Factors and Ergonomics (AHFE) 2012, USA, July 2012

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Chapter 1. Introduction

Industrial Revolution marked a major event in human history; almost every aspect of daily life was influenced in some way. It was during mid-18th and 19th century when manufacturing changed its form to an engineering sense of 'modern factory' rather than a local family business. Accordingly, the birth of manufacturing engineering and 'production system development' in particular can be appointed to that time period (Li and Meerkov 2009). During years a long way has been traversed, new paradigms have been established and new challenges have been raised in production systems and manufacturing sciences.

1.1 Simulation of Product and Production Systems

Even though the world has moved beyond the industrial age and into the information age, manufacturing remains an important part of the global economy. Highly competitive market and advances in production technology push manufacturers to design and produce more complex, higher quality products. At the same time, time to market is a critical success factor for the companies if they want to stay in the game. Therefore, increased complexity, higher quality insurance and shortened lead time are main driving forces to lead the productions systems into more efficient, less costly techniques of product development. Concurrent Engineering (Aitsahlia, Johnson et al. 1995) and Design for Manufacturing/Assembly (Redford and Chal 1994) are examples among many other methodologies to improve the production efficiency.

Prototyping is a common stage in most of the product development projects and can be either analytical or physical. As the physical prototypes are often very costly and time consuming, the developers intend to avoid it until the last stages of final design and thus more eager to use analytical prototypes such as simulation tools (Ulrich and Eppinger 2012). By using simulation tools, product developers can prevent unwanted changes in the design before it is too late. Also, comparing to physical prototypes it is easier to introduce changes in simulation environments so called digital mock-ups (Rooks 1998). Furthermore, simulation tools provide flexibility in handling product variations (Thomke and Fujimoto 2000).

Moreover, today simulation tools are not only limited to analytical prototypes but also simulating models of the whole production system. The resulted model is then employed to identify, analyse, and solve/optimize several types of problems which the systems will face in reality. Time compression, component integration, risk avoidance, physical scaling, and repeatability are numbers of benefits which are assigned to the simulation of production systems specially when there is high complexity in the system (Yücesan and Fowler 2000; Fowler and Rose 2004).

1.2 Human Simulation in Production Systems

Although human is an unavoidable member of most production systems, simulation tools neglected the integration of human into virtual production systems for many years. Complexity of human motions and computational and graphical limitations were major obstacles for such integration although the need to fully simulate and virtually run such production systems was always an initiative to consider and simulate the human. In this decade, the advances in computational capacity of today computers have changed the situation though (Van der Meulen and Pruett 2001).

Digital Human Modelling (DHM) tools are 2D or 3D computerized models which simulate human motions and actions in a virtual environment. The need to use DHM tools in the production processes often comes from big companies such as car manufactures. As a result, many of today’s process simulation software packages have integrated DHM tools into their software, one example is Jack from Siemens PLM software (Badler, Phillips et al. 1993). One of the first applications of DHM was to analyse if it is possible to reach a specific location or a control button (Ryan, Springer et al. 1970). Today, DHM models are commonly used during the design of a vehicle. Common industrial applications are to model the interaction between a driver, passengers and the interior in a car (Chaffin 2001; Yang, Kim et al. 2007; Reed and Huang 2008), analyse human reach and hand positions in manual assembly operations (Wenzel, Jessen et al. 2005; Mavrikios, Karabatsou et al. 2007; Zhou, Armstrong et al. 2009), evaluating workplace design in automotive assembly lines (Chang and Wang 2007), product design verification (Mavrikios, Karabatsou et al. 2007), ergonomic evaluations (Wang 1999; Woldstad 2000; Zhang and Chaffin 2005). A large sector of human simulation outside the industrial usage is entertainment such as games, animations and movies (Menache 2011), healthcare (Sen, Abboud et al. 2011), sport medicine (Neptune 2000), fashion and military clothing (Alexander and Conradi 2011).

1.3 Motion Capture Technology

Motion capture is a technology to record data-sets of human motions and has been widely used in animation and game applications. The recorded motions then can be applied to a computer manikin or animated character. It is used beside other techniques such as key framing to bring the digital character into life and control its movements. The technique is recently also employed in the industry in order to facilitate usage of digital human modeling tools when simulating workers in production lines. However, recorded data can be hardly reused because of unique nature of each motion.

1.4 Purpose and Aim

The purpose and aims of this work are to improve the usage of digital human models in the industry by:

- Providing new methods of using motion capture databases in order to increase the natural looking of the digital manikin motions
- Improving the functionality of existing DHM tools when simulating motions

1.5 Outline of Thesis

The thesis outline is divided into eight chapters. Chapter 1 -current chapter- discussed some background materials regarding the production systems and necessity of using simulation tools, and long absence of human in the simulation platforms. Driving forces for initiating this research and main objectives are also mentioned in this chapter. Discussion on the research purposes is continued in chapter 2 by pointing to the research questions which is addressed in this research also considering certain limitations.

Theoretical background of this thesis is presented in the chapter 3 titled ‘Frame of Reference’. To do so, five main contexts are introduced and important paradigms and theories of each area are looked through. The theory which is referenced in chapter 3 is connected to the research body through the research approaches described in chapter 4. In addition, different methodologies which are used in this research are also discussed in this chapter.

Chapter 5 provides the summary of outcome results and contributions made through appended papers. These results are discussed with more detail in Chapter 6 where several considerations regarding the methodology and results are provided.

Finally, Chapter 7 and chapter 8 are highlighting the answers to the research questions and concluding this thesis by mentioning further research. Full text of the contributed papers is also appended to the end of this thesis.

Chapter 2. Research Questions

This thesis and its appended papers are formulated around two research questions. These questions are concerning the facts derived from the reviewed literature and studying today's industrial DHM applications. It is observed that although many research projects embrace the profitability of using real human data for motion simulation in DHM tools, the existing motion capture data can be hardly reused in a systematic way. Moreover, availability of motion capture data for different applications provides opportunities to improve the look of generated motions in industrial DHM tools. However, generated motions in today's DHM tools are still looking unrealistic. Therefore, in this thesis two research questions are formulated in order to facilitate the usage of real human data for generating motions inside industrial DHM tools.

Research Question 1: *How can today motion capture data management systems get improved to be functional in DHM tools?*

Paper I -Schema for Motion Capture Data Management- has addressed this question and appended to the end of this thesis.

Research Question 2: *How motion design can be based on motion capture data to improve the look of motions in DHM tools?*

Paper II -Motion Synthesizer Platform for Moving Manikins- has addressed this question and is appended to the end of this thesis.

2.1 Delimitation

There are many different approaches employed by the researchers to simulate human motions. Two distinguished school of thoughts are physics/mathematics-based and real-data driven methods, which each of them in turn represents several techniques. The former includes inverse kinematics, regression models, joint stress optimization, statistical models, etc. and the latter includes data-base methods, motion warping, video captured techniques, etc. This research is categorized inside real-data driven methods and to be more specific, it is limited to simulate human motions using the data obtained from motion capture technology.

Furthermore, human motion simulation has been used in different applications such as military, game, animation, etc. This research is focused on application of DHM tools in industry especially automotive industry and to the commercial products existing in this area.

Different aspects of human can be considered as the purpose of simulation: appearance, biomechanics, cognitive, ergonomics, anthropometry, motion, posture, tissues and muscles functions, internal organs, etc. This thesis has not dealt with appearance, cognitive, anthropometry, and individual organs such as tissue, muscle, etc. but the focus is mainly on simulating posture/motion aspects of human while also considering ergonomics and biomechanical issues.

In some cases, the motion capture files which are used specially in film/animation can contain more than one subject in the single file (e.g. hand shaking motion). These type of motion files are not supported by the platform as the data handling will be more complicated but not very applicable to the industrial cases.

The context of this thesis is framed inside a number of research areas. The theories and paradigms of these research areas will be introduced in this chapter and will help the reader to understand the underlying foundation, which this research is built upon. The chapter starts with Biomechanics and Kinesiology of Human Motion which is important to recognize how the motion performs by real human and continues to Motion Capture Techniques and Data Management Systems which are describing different techniques of capturing and manipulating human motions. Next, DHM tools and their current scope of usage will be discussed and finally different theories on Motion Simulation Methods will be briefly mentioned (Figure 1).

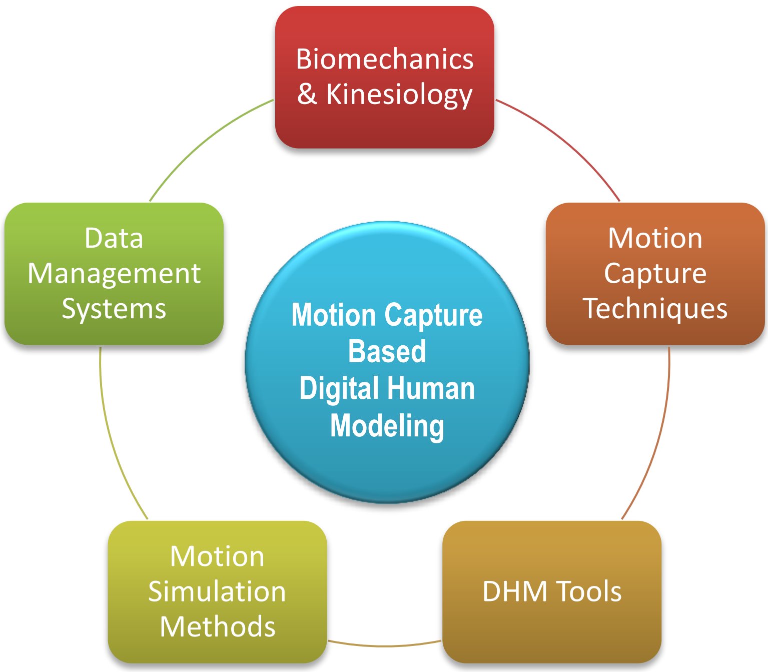

Figure 1. Frame of Reference

3.1 Biomechanics & Kinesiology

Historically, the word biomechanics is developed as an area of study across North America in early 70’s and is interpreted as mechanical properties of living tissues or the mechanics applied to biology. However, these types of studies go back much further to 17th century when Harvey[1], Galileo[2] and Santorio[3] formed the first concepts on blood circulation and attempted to express vital processes in terms of mechanics

[1] William Harvey (1578-1657): An English physician who was the first person to describe completely and in detail the systemic circulation and properties of blood circulation.
[2] Galileo Galilee (1564-1642): An Italian physicist, mathematician, astronomer, and philosopher who played a major role in the Scientific Revolution, he is called father of modern physics.
[3] Santorio Santorio (1561-1636): Colleague of Galileo and professor in medicine at Padua

(Fung 1993). Although the term mechanics can imply different characteristics, biomechanics by definition is limited to “the application of the *laws of mechanics* to animate *motion*” or “the study of forces acting on and generated within a body and the effect of these forces on the tissues, fluid, or materials used for the diagnosis, treatment, or research purposes” (Hall 2003). In addition, the term *Kinesiology* is used more often recently when referring to the scientific study of human movements (Hamill and Knutzen 2009).

Beside the biomechanical point of view to the forces generated/acting on human body, the study will not be comprehend if the causes and controlling system which the movements are originated from is not considered. This will lead to another field of study called Motor Control.

> *Motor Control: A field of study concerned with how sensory information from the environment and/or body is used in the control of movement and how such information allows an individual to select a movement (Schmidt 1988).*

And so in a very abstract form, biomechanics is the study of postures and movements while motor control is studying the mechanisms underlying them.

3.1.1 Theories in Biomechanics and Human Motor Control

For the control system of human movements from a higher level, several theories exist which the details are beyond the scope of this research. However, some of the concepts such as General Motor Program (GMP) (Rose 1997) which will be introduced later in this section explains a better understanding of how the motion is performed and how possibly it can be simulated.

From the control theory point of view, two different types of control mechanisms exist in the body: Open Loop Control which is used for short duration, well learned skills such as throwing an object, and Closed Loop Control which is used for more precise, longer duration actions and using sensory (afferent) data in order to close the feedback loop. Practically, closed loop control is applied to an executing motion to modify the plan of actions or to an already completed movement for registering successful motions as an experience which will be used in the future.

During years different theories are developed inside motor control area to explain different aspects of generated motions and some of them are briefly introduced here:

- **Reflex Theories**

According to this group of theories, reflex[4] is the fundamental unit of motor control and physical events occurring in the environment are served as the stimulus for

[4] Involuntary and nearly instantaneous movement in response to a stimulus

reflexes. These events are triggering chain of individual reflex-circuits that is responsible for producing a movement response (Schmidt 1988). During 1920-1930 various forms of *reflex chaining models* of motor control studied by people belonging to the school called *behaviourists* (Rose 1997). However, one weakness of these theories is that in many cases the actions don't need to be stimulated or at least not synchronized with the stimulus (e.g. when a hockey goal keeper predicts what will happen next). Second weakness is in describing movements in the absence of sensory feedback. Despite of the weaknesses, the theory has largely contributed in developing the treatment techniques called Neuro Developmental Treatment (NDT).

- **Hierarchical Theories**

The hierarchical theorists believe that when initiating an action, higher cortical centres command lower centres to carry out prescribed movements (Winter and Winter 1990). In this case, *Motor Programs* are pre-structured sets of motor commands developed in the cerebral cortex. A motor program which is previously stored in the memory, then being accessed and translated into neural command in order to be sent to the muscles. In support of the theory, De-afferentation studies which are surgically isolating the CNS[5] from one or both limbs and therefore cutting the sensory information about the organ, showed that the animal is still capable of performing the action. It means that there is a motor program which can be executed regardless of existence of sensory feedback information. Reaction Time (RT) studies also showed evidence of existence a plan before starting an action. However, the weaknesses embedded to these theories are that they cannot address the facts that individuals do not perform same actions always exactly in the same way as before, and storing every single program in memory needs huge amount of memory capacity.

In spite of mentioned weaknesses, the hierarchical theories present a very important notion in motor control called *General Motor Program*. GMP is believed to be a motion program forming in the CNS and consists of stored patterns of movements (Schmidt 1991). It is comprised of variant and invariant movement parameters where *Variants* assist us in varying a group of actions in a number of different ways. The *Invariants* provide us the ability to consistently reproduce the spatial and temporal features of a specific movement pattern once it has been learned. For example it is shown that "Relative Time" seems to be an important invariant in the movement patterns (Schmidt and Wrisberg 2000; Wright, Black et al. 2001). In addition, *Motor Equivalence*[6] also contributes in the formation of GMP. "The Writing Test"[7] performed by Raibert (1977) was a support for the idea.

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[5] CNS: Central Nervous System

[6] Motor Equivalence means that motor program is independent of the muscle group performing the task.

- **Dynamical Theories**

Dynamical theories distinguished from the previous theories by a number of basic but vital assumptions: Firstly, they propose that the system (human body) is self-organizing and so there are feedback mechanisms to adopt the motions to enhance the stability (Winter and Winter 1990). Accordingly, humans are adopting some preferred patterns of behaviour which are called *Attractor States* and are fundamentally based on keeping stability in the human system. Secondly, changes in movement behaviour can happen nonlinearly. These changes in preferred patterns are controlled by some *Control Parameters* while *Order Parameters* are used to identify the non-linear changes leading to the abrupt transition to a new pattern of coordination.

3.1.2 Characteristics of Human Actions

Based on these motor control theories, numbers of characteristics are recognized as common in most of human behaviours (Rose 1997). Although there is still a long way to fully apply and develop these features in digital manikins, they show a clear perspective of how they should look like. These distinguished characteristics of human actions are:

- **Flexibility:** doing same action using different muscles group. Example is using arm to write on a board and using hand to write on a paper. It is similar to what called Motor Equivalence in the previous sub-section.
- **Uniqueness:** no two movements are ever performed in the same way. It includes unique actions happens in new conditions which is not practiced at all before.
- **Consistency:** the temporal and spatial characteristics of an action remain relatively stable from one performance to next. In other word consistency is the ability to reproduce an action over and over.
- **Modifiability:** skilled performer's ability to modify an action even as it is being executed.

Among the mentioned theories about human motion, GMP is quiet well defined theory which can explain all the four specified human characteristics.

3.2 Motion Capture Techniques

Motion Capturing is a set of different techniques used to accurately record human motions in a way that can be applied to a digital manikin later. Among other existing

[7] According to the test, the same but ‘scaled-up version’ of program is running when one is writing in a small box comparing to when he/she writes on a big wall.

methods[8], optical Motion Capture is a known way to collect human motion data by using specific video cameras. Several different commercial Mocap systems are available today and can be categorized in two main groups: Active and Passive systems, which will be briefly described here:

The passive system is normally consists of set of special cameras sensitive to IR and a lighting ring surrounded the camera lens (Figure 2 - Up left). The ring emits IR light to the capture area and the lens receives the light reflection. The cameras are installed in a way to cover as much as the capture area from different angles. For capturing the motion, subject should wear a special suit with a number of reflective markers attached to it. The markers are normally placed on certain places of the body to facilitate the calculation of joint centres from three or four of the markers attached on the body surface (Figure 2). The accurate position of each marker in the space then can be triangulated by matching at least three images taken from different cameras and so the posture of subject.

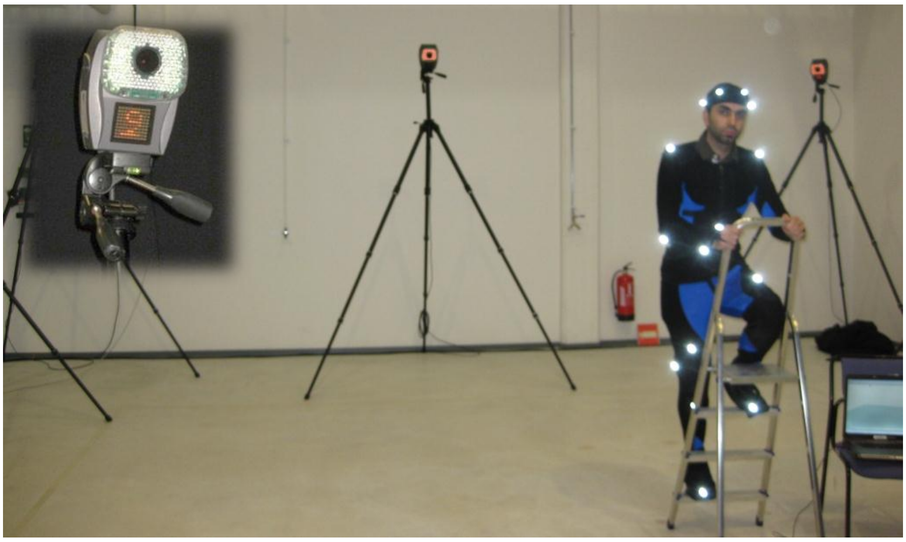

Figure 2. Optical Motion Capture Hardware Setup

The "active" motion capture technique is mainly the same but the markers are self-lighted with different frequencies. This causes the system to detect markers with less error when the number of the markers is increasing or when they are placed close to each other.

Furthermore, any motion capture system has a software interface connected to the described hardware setup. The main task of the software is to distinguish and track markers in real-time and calculate the position of each marker based on the images

[8] Other methods exist such as ultrasonic systems (Kitagawa and Windsor 2008), magnetic field systems (Yabukami, Kikuchi et al. 2000) and mechanical systems (Calvert, Chapman et al. 1982).

taken from cameras. Besides, the software is capable of deriving the joint centres and body segment's positions based on the detected markers (Figure 3).

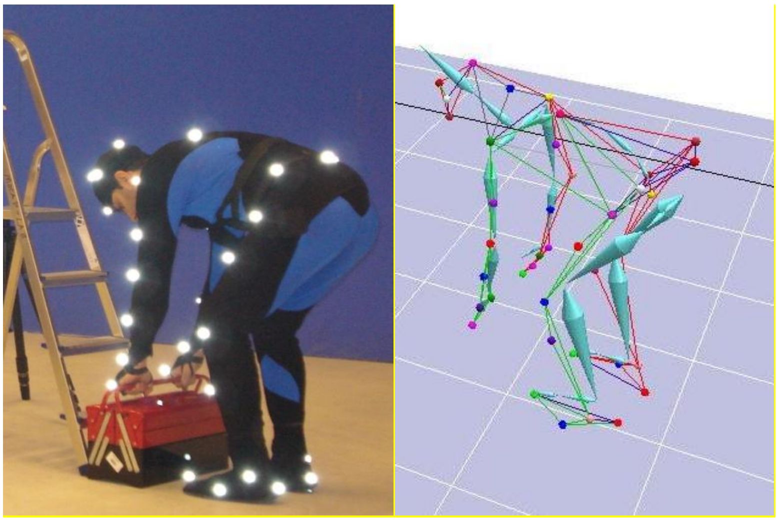

Figure 3. Left: Subject in special suit with reflective markers, Right: Detected markers and calculated body segments/joint centres for the same frame

The motion data generated in the MoCap software can be communicated in different formats. Global positions of markers (XYZ) and positions of calculated joint centres (XYZ) versus time (frame#) are basic types which are supported by all the MoCap manufacturers. Then, if a skeleton solver exists in the software, a more complicate but more useful data format can be processed from the marker positions. This format varies by each company standard but includes a structure for describing the body linkage system, length values for the links (bones), and values for showing joints angles changes during the time (normally in form of transform matrix). Despite the popularity of the MoCap technique among animators and filmmakers, there is still no unified standard on how to present the captured data[9]. Moreover, based on the application, different linkage systems may be defined to model the body motions. For example the spinal cord may be modelled from one to several links based on the needed flexibility. Also, the hand maybe modelled by one link if the finger motions are not essential to be modelled. These differences in file formats and models prevent users from efficiently employing externally generated motion capture files in their own studies.

3.3 Data Management Systems

A database management system is the system in which *related data* is stored in an *efficient* and *compact* manner. *Efficient* means that the stored data can be accessed quickly and *compact* means that the data take up little space in the computer's

[9] HTR-TRC (Motion_Analysis 2012), ASF-AMC from Acclaim, BVH from BioVision, and V3D (Vicon 2012) are examples of different file formats used in the market.

memory. The phrase "related data" means that the data stored pertains to a particular topic (Garcia-Molina, Ullman et al. 2002).

During the past decades, much research has been done on different methods of implementing such systems and several commercial products have been introduced. Today, database systems are very well established parts of the software engineering and their applications are visible in many other disciplines. Several models exist in database system theories which among them the relational data model is predominant choice in storing data, over other models like the hierarchical database model or the network model. In a relational database, all data are stored in tables and accessed via relations. Each table contains several fields and records whereas the relations are defining how the tables are connected.

In practice the tables and the relations between the tables are presented through diagrams called entity-relationship (ER) diagrams and then described in a formal language supported by the database management system referred to as database schema. In fact, data schema is a blueprint of how a database will be constructed (Figure 4).

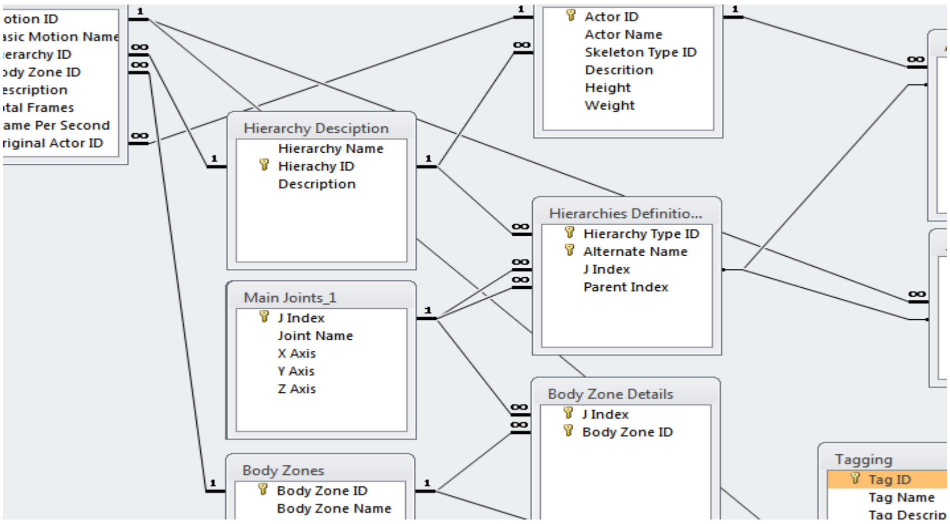

Figure 4. A view from a database entitiy-realtionship diagram. Tables, fields and how the tables are related can be depicted using ER diagrams.

Database systems should be able to not only store data efficiently but also shall provide ways to retrieve the stored data. This functionality is performed in database systems by generating queries. Query is a declarative language enables the user (can be an external application) to describe the desired data and leave the needed planning, optimizing, and physical operations necessary to produce that result to the database system. In this case, the user can be whether a front-end operator or can be an external application connected to the database and using the data for specific purpose. SQL

(Structured Query Language) is one of the most common programming languages used in relational database management systems (Wilton and Colby 2005).

3.4 Digital Human Modelling Tools

Digital Human Models in the context of this research are computer-generated representation of human beings developed in stand-alone software or integrated into CAD/CAM/CAPP[10] programs. The common feature of these models is the ability to graphically present human in different postures and to simulate human movements. Based on the application they can simulate and analyse the subject's actions from different aspects such as reachability, comfort, movability, ergonomics, line of sight, etc.

Computerized manikins in a broader perspective have been used widely in other areas. 3D animations and computer games utilized the technology to whether generate realistic motions for animated characters or apply the realistic motion to non-existing fictional creatures. However, the main concern in these areas is the graphical representation and rarely the accuracy of the model (Menache 2000).

Today, several DHM tools are commercially available on the market. These tools are providing functionalities which are needed to simulate human postures and motions while considering variations in anthropometrics features of the digital human body. Examples of such commercial tools are Jack from Siemens (Badler, Phillips et al. 1993), RAMSIS (Seidl 1997), Santos (Abdel-Malek, Yang et al. 2007), IMMA (Hanson, Högberg et al. 2010). Digital humans normally consist of a skeleton (connected links) forming a kinematic chain to handle body movements, 3D volumes surrounding the links which is representing body parts, and optionally a digital skin/cloth to increase the realistic looking of the model (Figure 5).

[10] CAD: Computer Aided Design, CAM: Computer Aided Manufacturing, CAPP: Computer Aided Process Planning

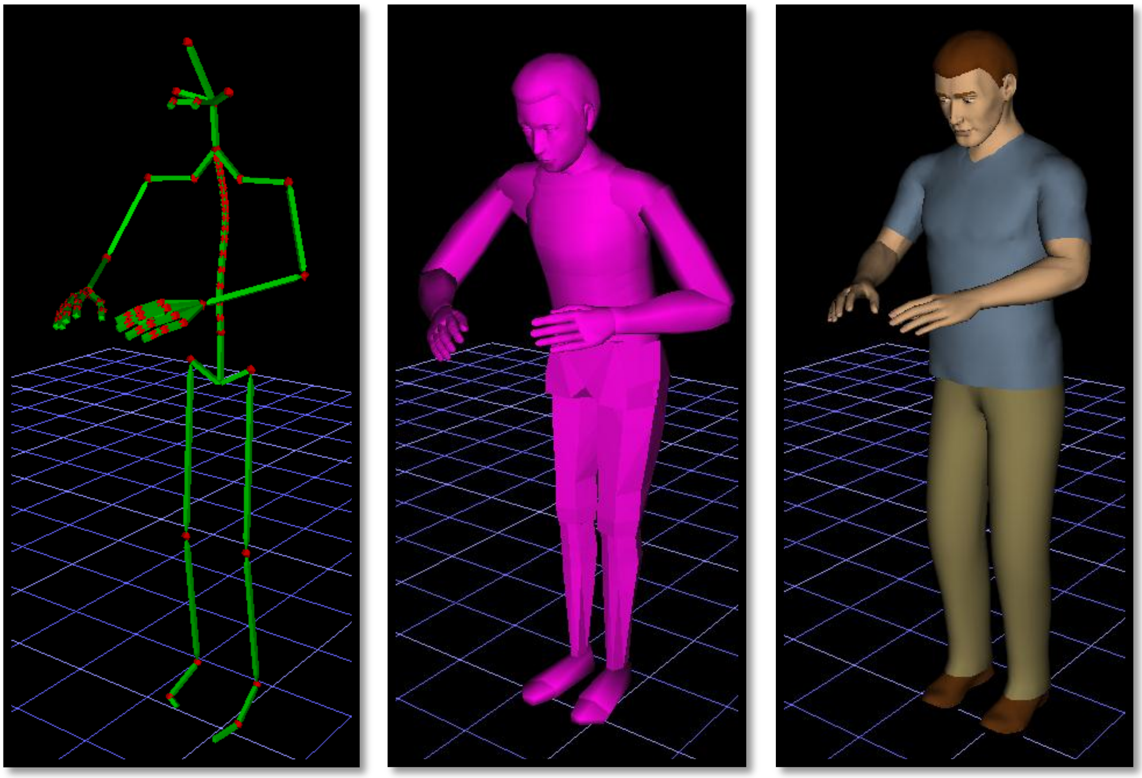

Figure 5. Different views of the digital human model
Left: Skeleton, Middle: Volumes, Right: Skin

3.4.1 Industrial Applications of DHM

Concurrent Engineering approach is increasingly being employed by major product developers such as automotive industry recently. CE approach is emphasizing on "front-loading" projects. This means to add as much knowledge as possible to the project as soon as possible by doing tests, verifications, and analysis (Ward, Liker et al. 1994). Accordingly, these early verifications of the design which are preventing late re-design costs and shortening the lead time of products, caused DHM tools to receive more attention from the industry (Chaffin 2005).

Industrial specifications of DHM tools distinguish it from different other applications such as entertainment. These specifications are: 1. In industry, ergonomics issues are concerned specially with populations of people, 2. The actions are happening in short time periods, 3. As an engineering tool it should produce consistent, repeatable and reproducible results (Reed, Faraway et al. 2006). To summarize, industry needs quantitative answers to the human-involved questions posed in the design processes from DHMs.

In particular, human plays two roles through the product realization process, human as a product user and human as a product manufacturer (Figure 6). The former affects how to design a product (Product Engineering) which is best suits human needs and the latter concerns how the product shall be manufactured with least negative impacts on the health issues of workers (Ergonomics and Work Environment Design) while maximizing the productivity (Production Optimization). In both cases DHM tools is similarly used to simulate human postures and motions.

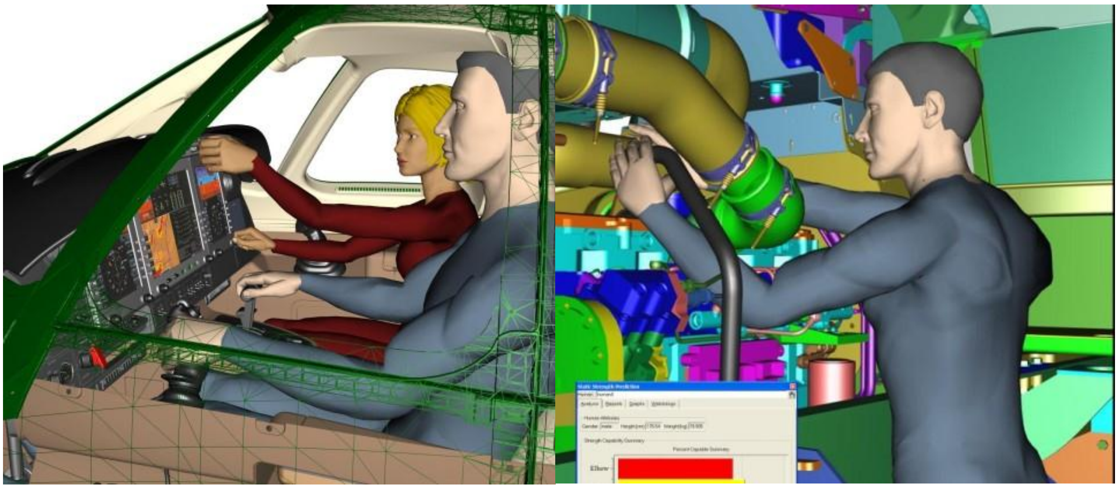

Figure 6. several roles of human through a product realization process,
Left: Human as a product user, Right: Human as a production worker

3.4.2 Usage

DHM tools are used in several industries nowadays. They are addressing numbers of problems which the design engineers are dealing with, without the need to have physical mock-ups. Some of these problems are listed here:

- **Reachability**

Digital human models can be utilized during product design stages to optimize the placement of control buttons or other accessories which shall be reached by the product users. It also includes the design of the production lines in a way that can be optimally accessed by workers with different anthropometric specifications. Accordingly, for each person, a space can be defined called *Reach Envelope* which is showing the range that can be reached by the subject. The unique benefit of using DHM tools is the possibility to test different populations based on the existing anthropometric databases (Woldstad 2000; Reed, Parkinson et al. 2003).

- **Clearance**

Although the reach envelope determines the allowed range to place objects, in many cases design issues are not coming from the reach envelope violation. Lack of access because of the presence of other obstacles is another problem which can be addressed by DHM tools. They are used for example to check if there is enough clearance to reach certain object suitably and if any valid postures exist in order to manipulate the objects in their working area (Badler, Erignac et al. 2002).

- **Line of Sight**

Several of DHM tools allow the user to view the simulated environment through the digital manikin eyes. This view allows the user to explore the environment for potential visual obstructions. Several studies show the importance of having clear line of sight in the productivity issues and the quality of final products (Rönnäng, Lämkull et al. 2004; Dukic, Rönnäng et al. 2007).

- **Ergonomics**

Work related Musculoskeletal Disorders[11] (MSDs) are a very common reason for job absence and it is very wide spread among manual assembly workers (Kuorinka and Forcier 1995). One of the major usages of DHM tools is to check human postures and motions from an ergonomics point of view (Woldstad 2000; Chaffin 2002; Zhang and Chaffin 2005; Chang and Wang 2007). Depending on the application, a number of standards exist in ergonomics to evaluate work postures, e.g. OWAS (Louhevaara, Suurnäkki et al. 1992), NIOSH (NIOSH 1981), and RULA (McAtamney and Nigel Corlett 1993). Tools have been developed inside DHMs to ergonomically analyse the performed motions based on these established standards. However, it is shown that the accuracy of simulated postures and motions have major effects on the result of ergonomic tool reports and in many cases the existing DHMs cannot provide accurate enough postures in a fast and consistent way (Lämkull, Hanson et al. 2009).

- **Time Measurements**

DHM tools can be used to perform time measurement analysis. The duration and required time to complete specific actions is automatically calculated by the software and reports are generated based on the calculations. It is similar to the method-time measurement (MTM), a technique used by production engineers in order to determine the time needed to perform a task. Moreover, ergonomics analysis based on MTM is also received more attention recently with the help of digital humans (Laring, Forsman et al. 2002).

- **Virtual Training**

Especially in automotive industry, training of manual assembly workers is an important issue and studies showed the effectiveness of using virtual training techniques (Malmsköld 2012). In this regard, DHM tools can be used for training purposes. Instead of working on real prototypes which in many cases is expensive, time consuming and not practical for large number of workers, animations or snapshots generated by DHM tools are used to show the assembly sequence/method

[11] The U.S. Department of Labour defines a musculoskeletal disorder (MSD) as an injury or disorder of the muscles, nerves, tendons, joints, cartilage, or spinal discs. MSDs do not include disorders caused by slips, trips, falls, motor vehicle accidents, or similar accidents.

(Lang, Xia et al. 2008). Use of training tools to teach proper postures can both improve the quality and prevents musculoskeletal disorders (Malmsköld 2012).

- **Musculoskeletal simulation**

Although kinetics of human motion has been studied for a long time, accurate modelling of performing forces on muscle tissues level is computationally demanding (Damsgaard, Rasmussen et al. 2006). By recent technological advances in computer hardware, it is possible to use digital human models to study and simulate motion dynamics and human kinetics on the muscle level (Wagner, Reed et al. 2007).

3.5 Human Motion Modelling

There are three major reasons why modelling of motions is necessary, as opposed to using a file of captured motion data directly to drive a digital human animation (Chaffin 2005):

1. Modelling can reveal patterns in complex data that are not readily apparent in the complex motion files and, thus, factors such as stature, age, gender, load being moved, etc. that most affect the general form of the data which can be inferred. This approach can lead to a more complete understanding of the underlying motor behavioural strategies and biomechanics that people use to control motions.
2. Modelling allows the prediction of how different groups of people coordinate the movement of specific segments of their bodies while performing a given task; that is, it provides a necessary distinction in general motion styles between subgroups for different tasks
3. Modelling provides the ability to predict motions under conditions that are different than the studied; that is, one can extrapolate the data to analyse novel situations.

Every DHM includes some inverse kinematics (IK) capability for posturing. Given a particular target in space for a hand or foot, the software will calculate the angles of the joints of adjacent segments to attain the goal. An extensive literature on inverse kinematics has emerged in the field of robotics. However, inverse kinematics alone can produce a posture, not necessarily a likely or accurate posture. Different methods have been suggested to generate a posture based on real human data. Examples are: using statistical models to perform regression analysis on the joint values (Faraway 1997), treating recorded motions as a manikin memory (Park, Chaffin et al. 2008) , warping an existing motion by adjusting the motion graphs (Witkin and Popovic 1995), synthesizing recorded data with the help of annotations (Arikan, Forsyth et al. 2003), and mixing recorded motions with inverse kinematic techniques (Aydin and Nakajima 1999; Faraway 2003).

Besides, some works have been done in computer animation and graphics to introduce efficient techniques for collecting and manipulating the human MoCap data. These works include database techniques (e.g. see Awad 2009), and annotation of motion sequences (e.g. see Kahol, Tripathi et al. 2006).

"The whole of science is nothing more than a refinement of everyday thinking"
Albert Einstein

A general research approach is firstly discussed in this chapter by briefly describing different research methodologies and their application. The scientific background on different research theories and their practical context help to better identify and locate the specific research performed in this thesis. Then, the next section of this chapter identifies research methods which were utilized through the papers and how the base of knowledge which is presented in this thesis was built up.

4.1 Research Methodology

A research work by definition is a *"Systematic, intensive study directed toward fuller scientific knowledge of the subject studied"* (Blake 1978). The systematic approach does not guarantee but increases the chance that the results of the research carry credibility, validity and hopefully reusability. In research theories, two methods of reasoning known as deductive and inductive reasoning describe how the theories, hypothesis and observations can be related in order to form a scientific approach to the research problem.

Deductive reasoning works from the more general to the more specific (Figure 7). Conclusion follows logically from premises, available facts, and arguments based on laws, rules, and accepted principles are generally used for a deductive method. Quantitative methods such as numerical estimation and statistical inference are examples of deductive approaches.

Inductive reasoning works the other way, moving from specific observations to broader generalizations and theories (Figure 7). Conclusion is likely based on premises and involves a degree of uncertainty. Observations tend to be more used for inductive arguments (Kuhn 1996). Qualitative Methods such as narrative description and constant comparison are examples of such.

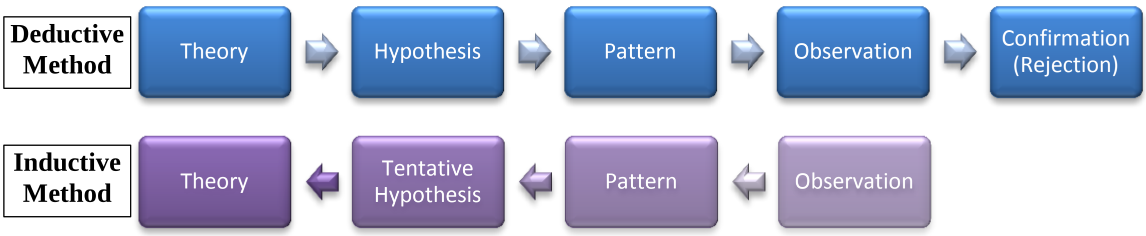

Figure 7. Deductive vs. Inductive Research

The practical relation between theory and empirical data is often a combination of both inductive and deductive approaches. The research starts with, for instance, empirical studies and a hypothesis is formed, next the researcher goes out in the real world to validate the hypothesis and then develops a more general theory. Accordingly, alternate models such as abduction model also exists which is a combination of the two previous models. While the first two approaches are more used in natural sciences such as physics/chemistry and formal sciences such as mathematics, the abduction model is more explanatory in engineering sciences (Burks 1946).

New research models such as *design science research* are proposed in order to better locate engineering developments inside existing research space (Vaishnavi and Kuechler 2008) and to value systematic system developments as a research methodology (Vaishnavi and Kuechler 2004). There are many cases which a systematic approach is employed to develop a research structure inside engineering fields and so in fact a research process is followed. Research work can be very generally considered as an activity that contributes to the understanding of a phenomenon. In the case of design science research, all or a part of the phenomenon may be *created* as opposed to naturally *occurring*. In here, a research methodology consists of the combination of the process, methods, and tools that are used in conducting research in a research domain while a research process involves understanding the research domains, asking meaningful research questions, and applying valid research methodologies to address these questions (Nunamaker Jr and Chen 1990). More important, in this multi-methodological model, system development is considered as a part of the whole research (Figure 8). Although this research model is primarily designed for Information Systems (IS) domain, it can be claimed to be representative as a general approach. In the multi-methodological model, the system development serves both as a proof-of-concept for the research and provides an artefact that becomes the focus of expanded and continuing research (Nunamaker Jr and Chen 1990). The model contains four main strategies named theory building, experimentation, observation, and the system development strategy in the centre. Each of the strategies also contains several stages which are serving as different tools helping the researcher to build up, test, verify and validate knowledge. It is important to mention that the classic research methodologies such as inductive/deductive reasoning are still broadly used inside different stages of the model but in a more flexible manner.

Finally, research can also be classified in various other ways. While there is much that is similar in these classifications, each shows its particular bias toward the nature of research:

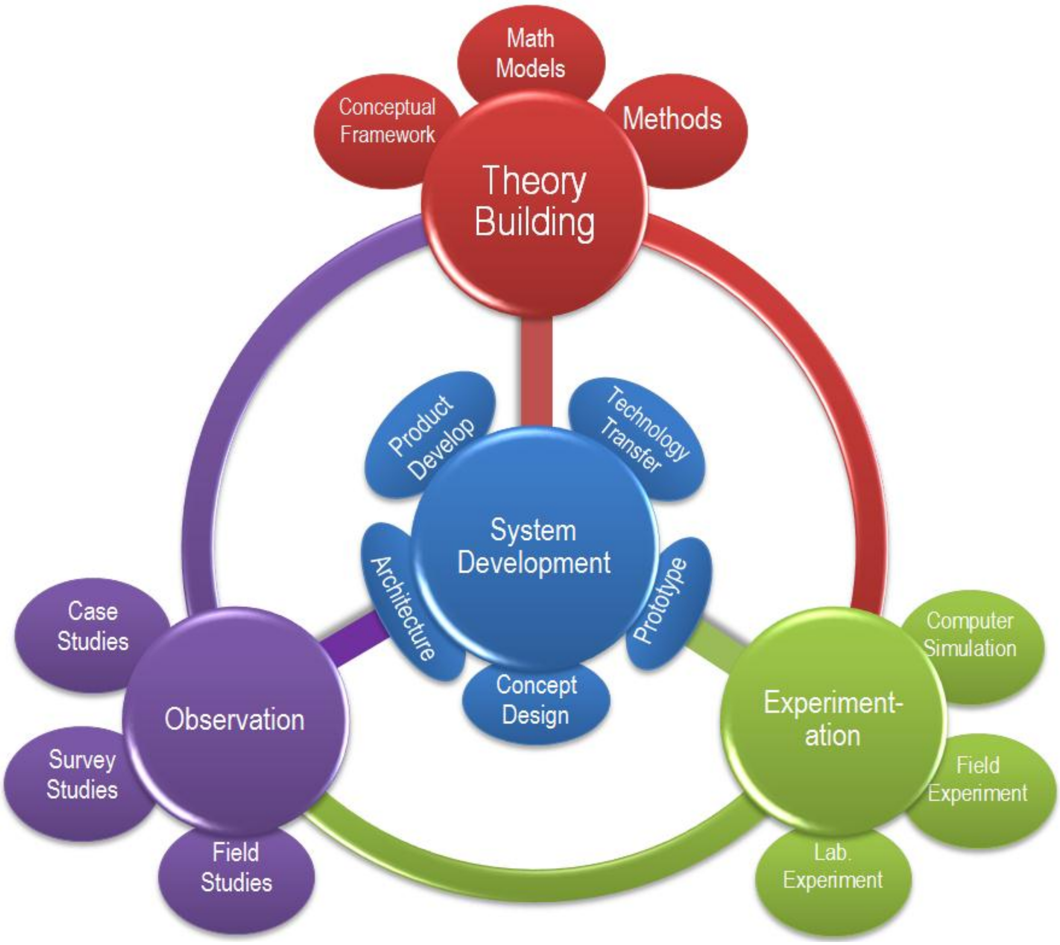

Figure 8. Multi-methodological Approach to Research, adopted from (Nunamaker Jr and Chen 1990)

- **Pure and applied research:** Pure research involves developing and testing theories and hypothesis that are intellectually challenging but may not have application in present or near future while applied research is trying to solve problems of immediate concern (Kumar 2005).
- **Basic, applied and experimental development:** Many of today's research activities are performed in the Research & experimental Development (R&D) units which are active inside business enterprises, governmental and private non-profit sectors. From the functional point of view, the types of R&D work in these sectors are categorized in Frascati manual (OECD 2002) as: basic research, applied research and experimental development. In this categorization, experimental development is a systematic work, drawing on knowledge gained from research and practical experience, which is directed to producing new materials, products and devices; to installing new processes, systems and services; or to improving substantially those already produced or installed.
- **Scientific and engineering research:** There is no logical distinction between the methods used by the engineer and those employed by the pure scientist.

Both types of researchers are concerned with confining their theoretical predictions. However, they differ in the scale of their experiments and their motives. In the engineering approach, the artistry of design and the spirit of "making something work" are also essential.

- **Formualtive and verificational research:** The goal for formulative research is to identify problems for more precise investigations and to gain insights and increase familiarity with the problem area while the goal of verification research is to obtain evidence to support or reject hypotheses.

4.2 Research Method

The research conducted in this thesis is fitting in the multi-methodological model which is described by design science research approach in the previous section. In addition, based on the above classifications, the research methodologies which are employed in this work are mainly fits into experimental development, engineering, and formulative research. Different research methods which are used in the two papers appended to this thesis are shown in Table 1.

Table 1. Methods used in Paper I and Paper II

Research Methods	Paper I	Paper II
Observation	Literature study Field study	Literature Study Case study
Theory Building	Inductive Methods Data models	Conceptual framework Simulation model
System Development	Concept design Architecture	Architecture
Experimentation	Computer simulation Lab. experiment	Computer simulation Lab. experiment

Each of the papers used different stages of four main methods depicted in Figure 8 and they are briefly described here:

4.2.1 Observation

Observation is often used when relatively little is known and it is desirable to get a general feeling for what is involved in a research domain (Nunamaker Jr and Chen 1990). Both paper I&II have used different observation stages to identify the knowledge gap and requirements for the new developed platform. In paper I, a literature study was performed on the different existing techniques to simulate human motion. Current situation of DHM tools and how the motion data are manipulated are also investigated. Paper II studied the requirements for an integrated platform to handle and analyse motion capture data, specifically to be used in DHM tools. A case study has also performed in paper II on comparing the results generated in the laboratory with the ones simulated in a commercialized DHM product.

4.2.2 Theory building

Theory building includes development of new ideas and concepts while they are centralized in a conceptual framework. Conceptual framework can be described as a set of broad ideas and principles taken from relevant fields of enquiry and used to structure a subsequent presentation (Reichel and Ramey 1987). Based on the observations, this framework was introduced in paper I around the concept of manipulating motion data and then it was extended in paper II around the concept of synthesizing new motions from previously recorded motion data.

4.2.3 System development

A part of this research work was dedicated to developing an information system prototype called platform in order to realize the concepts which were formed during theory building stage. At this level, prototyping is used as proof-of-concept to demonstrate feasibility. Paper I presented new data architecture (data schema) in order to manipulate motion data which was also utilized and extended in Paper II. This architecture was extended in paper II by adding new layers to the data schema presented in Paper I and it is introduced as an integrated prototype called motion synthesizer platform.

4.2.4 Experimentation

To test the functionality of the data schema which is presented in paper I and the motion synthesizer platform which is presented in paper II, a number of experiments was performed. The experiments in paper I include laboratory recordings of real-human motions using motion capture technology in order to ergonomically test and validate those motions. In paper II, real human actions were generated in the laboratory and then as a case study they were simulated and compared using computer software.

The research process which is stated in Figure 9 has led to two papers which are included and their full texts are appended to the end of this thesis. Both papers are presented in digital human modelling conferences and have been published in their proceedings series. These papers mainly concern the efforts to introduce the concept-forming, development and test of a motion synthesizer platform capable of handling and reusing motion-captured data.

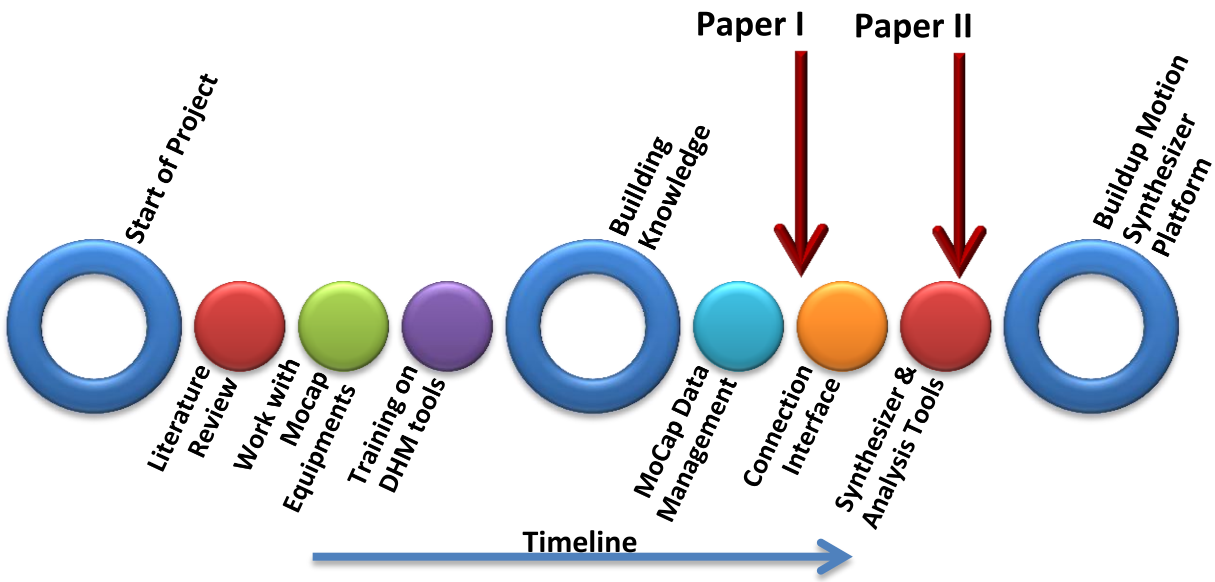

Figure 9. Research Process Overview

5.1 Relation between Papers

What can be summarized so far from the discussed problems and issues are the following statements:

- Solutions based on real human motions need a reference motion close enough to the desired scenario in order to change and retarget it to the new conditions.
- It is impossible to record all possible motions of human being, for they are infinitive combinations.
- Even having huge amounts of recorded motions, they shall be efficiently stored in order to be searched and reused later on (longer lifecycle).

Concerning these statements, this research contributed to the subject by suggesting a conceptual framework and implementing a platform. The platform can provide certain functionalities in order to facilitate usage of motion-captured motions in DHM tools. It is considered as an essential foundation which is needed for the research continuation on the integration of real human motions into DHM tools.

This platform which is called motion synthesizer is introduced, implemented and evaluated by means of the two appended papers. From the functional point of view, paper I is describing the core layers which are handling data management (yellow and orange layers in Figure 10) and paper II is describing the application layers (red and blue layers in Figure 10) and also the interface between these two parts. The grey part in Figure 10 depicts possible examples of extending the platform.

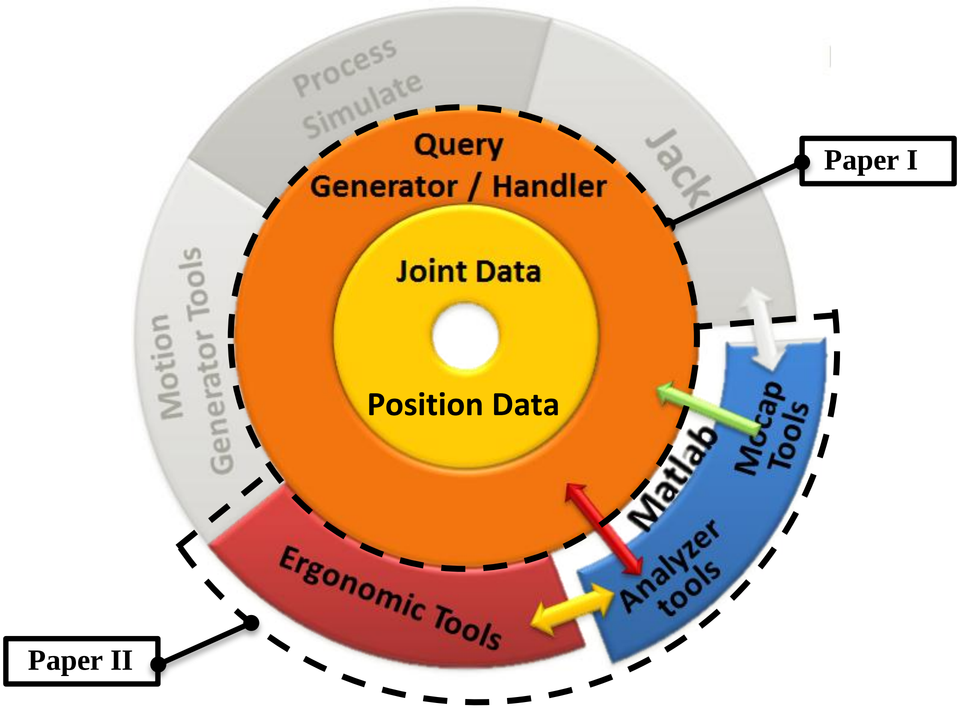

Figure 10. Relation between contributed papers

5.2 Paper I: Schema for Motion Capture Data Management

The literature which has been reviewed in this paper formed the following statement:

Simulating natural human motions is not an easy task. Redundancy caused by additional degrees of freedom, restrain conventional mathematical solutions. It is identified that motion solving algorithms based on real motion captured data is one promising solution.

Normally, captured data is kept in large data-sets and reused later to generate new motions. Nevertheless, in compare to animation projects which are mostly involve manual adjustment of the existing motions, industrial usage of DHM tools is more sophisticated. Selected motions have to be analysed from different aspects, such as posture, reachability, and ergonomics. Moreover, finding a reference motion shall be done automatically and the motion segments shall be suitably marked with unique identifying annotations. Since there is low compatibility between different databases and the search criteria are limited to one set of data, asking same query from multiple databases is very complex. Reasons for incompatibilities can be differences in: naming conventions, skeleton definitions, file formats, data structures, storage methods, etc.

To overcome the stated problems, a model contains an application layer, and a database schema is presented in paper I. Also a workflow is suggested based on the implementation of the data schema. The aim of this model is to improve the reuse of motion captured data in industrial applications. Improvement includes extended annotating system, improved search capabilities, connectivity to visualizing tools, access from different applications, and updating the database with value added results. This data management layer will be further used in paper II in order to synthesize new motions by combining existing motion segments stored in the database.

For the implementation, a two layer solution, “Front-end and Back-end”, is suggested. Front-end layer can be any application, and in this project MATLAB was used. The Back-end data storage system was implemented using standard Microsoft Access DBMS. The data schema was designed to handle several objects, such as joints, skeletons, motions, body regions, postures, and annotations in the database. These objects defined the human motion accurate and clear enough to answer all types of queries generated from Front-end application layers.

A number of features were considered for the schema:

- Support of multi skeleton definitions
- Flexible definition of body regions (upper body, lower body, right hand, diagonal limbs, etc.)
- 2D annotating system
- Categorized annotating

Based on the application, different skeleton types can be defined, but all will be treated uniformly by the query manager. For example when the Front-end application asks for a specific action performed by right hand, the database returns matching answers regardless of how the right hand is defined in different skeleton types. Moreover, by defining and marking of customized body regions, the system is guided to recognize which body parts are important to perform a specific action. Accordingly, when searching for a key posture, the chance of losing a valid posture because of incompatibility in non-important body regions is minimized. A new annotating system is also introduced for motions not only in time scale but also on specific body regions categorized by the related application.

To assess and validate the proposed concept, two tests were performed. The first test was to generate sequences of motions in our motion capture laboratory and feed them to the database. A generic joint set and an a priori defined skeleton in the data schema were applied to these sequences of motions.

Secondly, several motions with different joint configurations and skeleton definitions from other sources on the net were fed to the system in order to test the multi-skeleton compatibility. Several body regions were defined on the skeleton sets and each motion was manually annotated based on the performed action, involving body regions, performer gender, load conditions etc.

Secondly, MATLAB software was used to access the database for testing the connectivity between Front-end and Back-end layers of the system, to ask a query, analyse the received motion based on an ergonomic standard (e.g. OWAS), find possible invalid postures and update the database with new annotations. The tests showed successful results and the established connections were consistent throughout the procedure. Furthermore, this platform was capable of supporting different motion formats, various skeleton types and distinctive definition of body regions in a uniform data model.

5.3 Paper II: Motion Synthesizer Platform for Moving Manikins

This paper presents a motion synthesizer platform which aims on simplifying the demanding task of generating natural-looking motions. The synthesizer platform which is presented in this study is able to store motions taken from real human in a database and synthesize new motions using these already existing motions. It is based on the hypothesis that a new motion scenario can be generated by using multi-sourced pieces of old motions and applying them to different parts of the digital body model. These needed motion pieces in some cases can be found in existing motion files on the net. This platform can be served in future as a connection bridge between DHM tools and motion capture databases and it is able to search the database, analyse the data, and feed the data to DHM tools.

The platform consists of three connected layers (Figure 11):

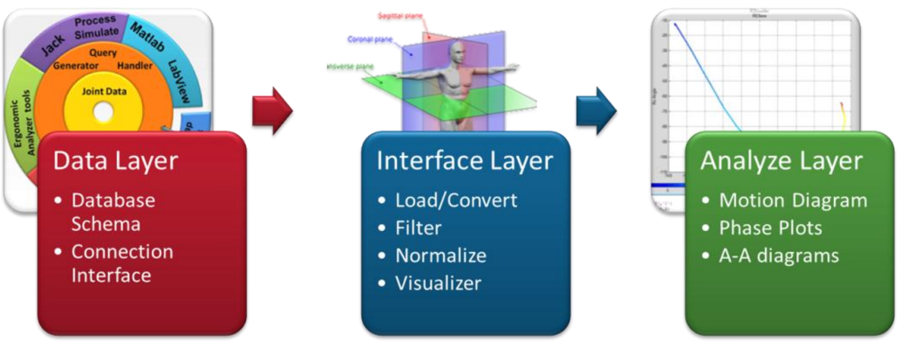

Figure 11. Different layers of Motion Synthesizer Platform

Data Management Layer (DL): This layer is based on a data schema implemented in paper I and works as a core module for the whole platform. It indexes joint centres both by joint values, and joint positions relative to the base of the body and provides the following functionalities:

- Storage, search and retrieval of motion data with support of multi skeleton configurations
- Customizable definition of body regions, e.g. upper body, right hand
- Categorized spatial (body regions) and temporal (time frame) annotating system

Interface Layer (IL): This Layer which is implemented in Matlab enables the user to synthesize new motions matching a target scenario from the DL. The synthesizer gives the end-user tools to cut/join motions along a time frame, to squeeze/stretch a part of a motion to the desired length, to split motions from a part of a body which is doing a specific task and combine different parts of different from different subjects to build up new motions.

Analyse Layer (AL): Beside the motion knowledge which is embedded in the DL using annotations, further analysis of the motions are done in this layer by a number of analysis functions implemented in Matlab. These functions include study of Angle-Angle, Angle-Velocity, and Velocity-Velocity diagrams of coupled joints. Relative phase, phase portraits, and kinetic energy diagrams are also available for the user. In general, these functions enable the user to study and compare joint motion characteristics, and if necessary manually coordinate the joint motions.

Two different experiments were designed to measure the platform functionality: a) one experiment was aimed at Interface Layer and its synthesizing functionality by composing new motions by combining upper-body motions and lower-body motions from two different subjects and b) next experiment was tested the Analyser Layer by using analysis tools to compare generated motion in commercial software against captured motions from real human. To do the experiments, a number of Humosim lab experiments in LOC (global joint locations) file format from Michigan University and motions created in our own lab in HTR (Hierarchy Translation Rotation) file format are imported into the platform.

Chapter 6. Discussion

This research work is built upon two tracks: Motion Capture technology and Digital Human Modelling tools. Each of these tracks has been developed by several applications during the past years; nonetheless a major integration has not happened yet at least in the commercial market. Besides, the academia has been recognized this need for integration and several attempts have been made to integrate motion captured databases inside DHM tools. Why these attempts were not ended up in a successful software application yet is a question that is discussed here:

Motion capture technology is a well-established tool in health care science (physical rehabilitation), sport research (motor learning), and animation/game industry. Each of these fields derives certain features from the recorded motions; health care science is more focused on cyclic motions such as gait and in most cases single subject comparison is the base of judgement to notice changes in physical improvements of the subject. Quantitative assessment of movement is important in determining the functional status of patients immediately after neurological injury in order to aid the determination of a pharmaceutical or therapeutic treatment regimen. On the other hand, sport researchers are more concentrating on energy consumption and general motion patterns although they consider multi-subject studies. Sports medicine and performance analysis go hand in hand with analysis aimed at preventing injury. While the protocols are often very similar, the analysis of sports related movements often entails analysing a variety of highly dynamic movements. Finally, game and animation industries are recording motions based on pre-defined, highly controlled and target oriented scenarios, which means that generalization of those motions is rarely intended. In total, what can be concluded is that in most cases the motions which are generated by motion capture systems in these applications have very short lifecycles; rather they are very specific to a scenario or very focused on one subject.

On the other hand, DHM tools are more directed to industrial usages such as ergonomics, manual assembly, reachability which are demanding capabilities to handle anthropometric variations (manikin families) and motion/task generalization. In other words, while the traditional usages of motion capture technologies embrace subject limited and task oriented motions, DHM tools are seeking for more generalized motion patterns which are applicable to a wide range of manikins/tasks. Moreover, the motion scenario which should be simulated during a sample process is totally unpredictable and very dependent on many parameters such as the geometry of the scene, needed actions and task specifications. Therefore it is not practical to predict and record these motions beforehand.

6.1 Methodological Considerations

6.1.1 Reasoning

The practical relation between theory and empirical data is often a combination of several reasoning methods. For instance, in paper II a hypothesis is formed on the idea of 'if motion capture can improve the natural look of digital manikin movement', next the hypothesis is validated by performing some experiments and then a more general theory on how to apply changes in order to have a more natural looking motions is presented. The nature of these types of reasoning implies that these theories which are built on the results of experiments are true for the stated conditions of experiments and hopefully a reasonable range outside until they are falsified in the future.

6.1.2 Data Collection

The motion capture data which is used in this research was collected from different sources. Part of these data is coming from the in-house motion capture laboratory at PTC. This laboratory is equipped with an optical motion capture system from Motion Analysis Company. The facility includes 10 Hawk® cameras surrounded a capture area of 4x5 meter, special suit with reflective markers, Cortex® and Tecnomatix Jack® software. In general, when using optical motion capture systems, a number of issues shall be considered:

Post-Processing: When performing full-body motions, normally around 50 markers are used on the body based on a pre-defined template. In order to simulate the subject motions, these markers shall be detected and tracked. Although the software utilizes complicated algorithms to distinguish these markers, they can be covered in some moments or getting very close to each other leading to errors in identifying them correctly. Therefore, for most cases a post processing stage is needed to treat the marker's data. This initial post-process can greatly affect the quality of final resulted motion

Mapping: Marker's data shall be mapped to the subject skeleton in order to calculate the joint centres. The accuracy of the results is greatly affected by the composition of subject skeleton in the software (number of joints-segments), calibration of the skeleton dimensions to real subject, and optimization algorithms which is used to calculate joint centres. Some algorithms allow the segments length to be varied in each frame while others not, some considering the real DOF of joints (e.g. one DOF for elbow joint) and some not. The experiments used in this research were treated by software internal optimization engine on a 27-segment skeleton, assuming fixed bone lengths through the motion, and applying joint DOF restrictions on the skeleton.

Data Export: It is possible to export motions with different settings. It can be global positions of the calculated joint centres, global positions of the skin markers, global position/orientation of body segments and relative hierarchical position/orientation of body segments. The latter was chosen here because it is closest to derive Euler angles from. Then the joint centre positions are recalculated and added to the database later on using developed functions in the synthesizer platform.

Subjects: Subjects which is performing motions were chosen randomly among colleagues including the author (total of 6 subjects; 5 male, 1 female). As the purpose of the experiments was testing the functionality of platform and not analysis of the motions itself, no specific consideration made for the selection of subjects.

External Sources: Rest of the data which is used in the experiments are taken from different sources available on the net. Big part of this external data is coming from a collection of recorded motions in HUMOSIM laboratory of Michigan University (Reed, Faraway et al. 2006). These data-sets are categorized into numbers of different experiments (e.g. reaching a point while seated or lifting objects) performed by several subjects and stored in the form of file datasets in separate folders. The storage format is global position of joint centres. The skeleton configuration consists of 19 segments for stand position experiments and 9 segments for seated experiments. These data is imported to the synthesizer platform and converted to Euler angle format using a number of implemented functions in the platform.

6.2 Discussion of Results

6.2.1 DHM-Oriented Databases

Paper I which is presented after a literature review period serves two purposes. Firstly, it should be seen as a study which is pointing to the gap which exists in the domain and secondly as a first step -which is further continued in paper II- in order to fill-in this gap which is discussed here:

To generate and simulate human motion for industrial applications, there are several techniques existing in the literature which are using real human data as a root motion (Yamane, Kuffner et al. 2004; Park, Chaffin et al. 2008) or using motion captured datasets/databases as the source of generating motions (Aydin and Nakajima 1999; Kovar and Gleicher 2004; Lin 2006; Nguyen, Merienne et al. 2010). Without exception, the extensiveness of such datasets has direct effect on the performance of the proposed algorithms. However, most of these techniques are assuming that such a motion database is already exists, and can be utilized in the motion generation algorithms; which is not precisely true. To the author’s knowledge, there are very few platforms that have collected large amounts of motion captured data specifically for the DHM tools. Example of such platform is the Humosim Framework (Chaffin 2002; Reed, Faraway et al. 2006) which is developed for automotive industry. Even in these cases, embedding of motions from external sources is not well-supported and the system is dependent on short motions containing single tasks. In other cases, a small collection of data is gathered mostly by in-house lab to test and validate the proposed technique in a limited context (Zordan and Hodgins 2002; Beurier, Chevalo et al. 2007). Because of this limited context, no direct attention is also paid to the importance of having well annotated motion pieces. Moreover, in these cases it is crucial to have well-organized motion ‘databases’ rather than a large motion ‘dataset’ which is a big collection of captured files normally categorized in several folders based on the main action performed by the subjects. These ‘datasets’ are very common in the film industry; because the data treatment is mostly done manually and therefore a sophisticated database system is not needed. Therefore, the need for having a comprehensive platform which can gather motion captured data from different sources as well as organizing them in a proper way that can be automatically utilized by motion generation techniques has been identified in this research.

The experiments performed in paper I are all designed around a main purpose: showing that the proposed platform works as it should. Therefore these experiments shall be considered as the ‘proof of concept’ rather than independent test cases. It was of great importance to check if the key requirements which were explored during the literature review period are served well by the platform. These key functionalities (KFs) were:

KF1. Support of multi-configuration skeleton definition
KF2. Support of two dimensional (spatial-temporal) annotation system
KF3. Support of customized body segmentation

The first experiment (Data Update) was performed by importing several motions with two different body configurations (KF1) into the database and defines new body segmentation needed for OWAS analysis: Back, Upper Limbs, and Lower Limbs (KF3). Second experiment (Annotation Report) used the data in previous experiment to analyse imported motions from OWAS standard point of view and reflect the result of this analysis back to the database using two dimensional annotation tool (KF2) and finally last experiment (Visualization) was used to proof that firstly the platform is able to connect to other applications and is not a stand-alone tool and secondly, stored annotation can be used to search for different types of queries (KF2).

6.2.2 Motion Synthesizer

In paper II, a motion synthesizer platform was presented. One purpose of this platform is to support the data-schema layer which is presented in paper I by means of necessary tools and functions to manipulate motion data. Accordingly, the platform plays the role of an interface which is facilitating the transfer of motion data to the database and also makes a bridge between motion database and other applications. Other than this, the platform is also functions as a motion generator by synthesizing new motions from pieces of other motions already existing in the database. Although the idea behind is quite simple, several considerations have to be thought:

Re-subjecting: The platform enables the end-user (which can be a human user or an external application) to apply the motion which is performed by one subject to a new subject with different anthropometric specifications. This should be done with awareness of possible implications. Firstly, joint's range of motions (ROM) varies on different people. Healthy/unhealthy, male/female, old/young, thin/fat, tall/short people have different range of motions (Steenbekkers and Van Beijsterveldt 1998). Therefore, applying of motion from one subject to another shall be done with awareness of such variations especially on joint boundary values.

Re-targeting: Motion re-targeting -also known as motion warping- is to play with motion curves of individual joints, in order to change the start position or end position of a segment (Witkin and Popovic 1995). Normally, distal segments such as hands or head are the purpose of re-targeting and this technique is usually used by animators. However, the base of judgment for validity of such a change in motion characteristic is the visual feedback and feeling of the animator. It is possible to use this technique in the synthesizer platform in order to adjust the initial/final positions of segments but further attention should be paid. Firstly, the intention of using such platform is to automatically generate new motions without the need of manual work. Hence it should be applied in a more systematic way that no visual feedback will be needed to check the natural looking. In most of cases it is ok to use the technique when there is a small difference between the current and desired position and the joints are not close to their upper/lower limits. Secondly, generated motion should be rechecked from ergonomics point of view as it can be affected by the re-targeting.

Re-coordinating: The platform has the capability to blend motions taken from different files for different parts of the body. We have shown in our experiment that for certain simple scenarios this method is working well and creates natural looking motions though it is computationally inexpensive and therefore worth to focus (see paper II). However, the conditions which different parts of the body (e.g. upper/lower body) can be moved independently should be further studied. In many cases such as walking the motion of lower and upper limbs are coordinated by the brain and shall be considered when blending two motions. In periodic motions such as walking/running the coordination between arms and legs has been studied by gait analysers (Perry 1992). Also sport medicine scientists have done limited cases research on non-periodic movements such as golf swing (Burden, Grimshaw et al. 1998), baseball pitch (Fleisig, Andrews et al. 1995; Hong, Cheung et al. 2001), etc. but no global concept exists which can be applied to general cases. The platform provides tools to analyse this coordination manually between coupled joints but still unable to automatically detect and coordinate the cases which need to be treated.

6.2.3 Orientation Presentation

In paper I, a database schema was implemented where part of the schema has the task of storing motion data in the form of changes in joint angles. To do so, using of transformation matrices is a natural way to describe position and orientation of rigid body segments globally, or relative to their proximal segment. Many of motion capture file formats such as HTR from Motion Analysis (Motion_Analysis 2012) and ASF from Acclaim are also using similar methodology to record motions. However, in order to save space, the transformation matrix itself which is a 4x4 matrix is not directly stored. The transform matrix can be decomposed to two other matrices: A translation matrix to describe relative position and a rotation matrix to describe relative orientation. Based on Euler theory, to describe orientation, any rotation matrix can be decomposed to three independent rotations around a single axis. These three angles can be described in several ways; a common way is to use Euler-angle convention in which three variables are describing the rotation around three non-similar axes (e.g. ZYX). As the transform function is not-commutative, the rotation order is also needs to be stored (in the data schema it is stored in a table called *motion header* under the field *RotationOrder*). For the translation matrix part, two more assumptions have been made: the bones (segments) are considered to be aligned on one of the frame axes (it is normally Y axis and mentioned in the motion header table by *BoneAxis* field), and the length of the bones (segments) are assumed to be constant during the motion period. Accordingly, to describe a motion, there is no need to store the relative position of each segment (which is equal to the length of proximal segment in the *BoneAxis* direction) for each of the frames and they need to be stored only once for each subject. To summarize, to store any motion based on the mentioned assumptions the following data is needed:

- A table describing the hierarchy of the body segments (hierarchy table)
- A table describing the segment lengths and their initial (frame 0) relative positions (base frame table)
- A single value defining the *BoneAxis* (motion header table)
- A single value defining the Euler rotation order (motion header table)
- A table containing three rotation variables per each frame of the motion (joint data table)

This method of storage has number of benefits:

1. Except the joint data table the other tables are small and taking little memory space. A great amount of space is therefore saved by storing just three variables instead of a 4x4 matrix in the joint data table.
2. The numbers in the joint data tables can have physical meanings. For one DOF joints such as elbow the stored variable is simply the joint value.

However, use of Euler angles shall be further investigated. In comparison with other methods of describing the rotation and translation such as quaternions, the Euler angles are computationally more expensive. Besides, while implementing some of the motion synthesizing functions in paper II (e.g. the stretch function); difficulties were noticed in order to interpolate the Euler-angles rotational data. Using quaternions is more beneficial in blending and interpolation of rotations (Shoemake 1985; Choe and Faraway 2004). On the other hand, four parameters instead of three are needed to store rotations in form of quaternions which means more memory consumption.

6.2.4 Annotation Tables

Annotating motion files is a common way to describe the contents. Usually these annotations were used by animators to do segmentation of different actions performed in one file. In these applications, as the rest of the job is normally handled manually, no need felt to assign what part of the body has performed the task (spatial) and so only the start/stop frame is stored (temporal). Exceptions exist such as in choreography when the performing segment is of great importance and so both spatial and temporal information shall be stored (Kahol, Tripathi et al. 2006).

In the cases which need automatic searching of motions such as in DHM tools, one dimensional annotating causes a major problem: assuming the system is looking in the database to find range of frames matching a posture while doing a specific task; if the system does not know from the annotation table that which part of the body is the major concern to perform that task, there is a chance to miss proper frames because of mismatches in the non-essential parts of the body.

The annotation system developed in this research uses the annotation tables not only to store information about actions but also to store other information which is gained gradually about the motions as a result of different analysis. Example of such information is the results of ergonomic analysis and/or the load which is carried during a lifting task. These types of information can be embedded to the motions in form of annotations in three domains: global domain (e.g. the entire motion is performed by a female subject), temporal domain (e.g. the subject carry loads during certain time range), and spatial domain (e.g. the load is carried by the left hand).

Current solution is indexing motion data based on both joint values and joint local positions (relative to the base of the body). Direct effect of such implementation is that queries to check if a segment is in a specific space (e.g. all frames that the elbow joint is upper than the head) or queries to check if a joint is in a certain range (e.g. all frames that head is looking straight) are easy to handle. However, the drawback of such implementation is the large amount of memory occupied because of indexing joint values in all frames. One solution to this problem is keeping the specification and annotation information of motions in the database but keeping the joint values as an attachment to the database. In this method, the primary search result is refined based on the information in the annotation tables and then only the necessary joints data is loaded and indexed for a limited number of results (Load on Demand).

6.3 Implications on Commercial Tools

The second experiment in paper II was focused on the comparison of a sample motion performed in a commercial DHM tool with the same motion acted by a real human. Although the selected motion was a single, simple and straight forward action (regular walking forward); major differences were found in the way that the DHM tool simulated the action: shoulder joint motion was not similar to the one in real human and the elbow joint does not move at all during performing of the motion. One reason of such big difference can be that up to recent years the major concern of the DHM tools was simulating and studying the postures and not the whole motions. In this regard, simulating the motions was more an extra functionality and the natural looking of these motions was not the primary concern. This means that still major improvements needed to be done on the existing tools to increase natural looking of the motions. We have shown in our experiments that some of these improvements such as modifying the arm movements while walking can be simple but effective at the same time.

It should be mentioned that some of the today's DHM tools on the market are supporting motion capture plugin. In these tools, a digital manikin can be assigned to follow the motions of a captured subject in real time. Normally a type of visual feedback such as a head-mounted display visualizes the scene for the human subject during the performance so he/she can see himself/herself inside the simulated environment. However, this is not what is preferred in this research as it is still using motion capture for a single-subject, one-time usage, and scenario-oriented application.

Existing commercial DHM tools are mostly used to visualize postures rather than motions. It is concluded that although motion generation functionalities are also embedded in them, simulated motions of daily tasks are still looking unnatural. For a sample test, the analysis tools which are developed as parts of the synthesizer platform identified some of the major differences existing in the simulated motion compared to the real one. It is shown that these differences are accounting greatly for the unnatural look of the simulated motions.

Chapter 7. Conclusion

Two research questions have been addressed in this thesis. The results from the work have been discussed in the previous chapters and are concluded here as an answer to the proposed research questions.

Research Question 1: *How can today motion capture data management systems get improved to be functional in DHM tools?*

While DHM tools are seeking for generalized motion patterns which shall be applicable to a wide range of manikins/tasks, today's motion capture data in other applications than DHM tools found out to have short lifecycles, mostly specific to a scenario, or focused on subjects. To facilitate motion simulation algorithms which are using real human data as a base, it was found that existing data collecting tools are not efficient. To make motion captured data functional for DHM tools, these data shall be stored in databases (and not data-sets) which are supporting specific features. These features are identified as:

- Support of variation in subject's configuration
- Support of body segmentation
- Support of information integration about motions
- Support of motion format variation

A schema for such database was devised, developed and validated in paper I. It was shown that such solution is beneficial to be used in DHM tools implementation as it is able to organize, search, and reuse motions which are created by different sources and with different specifications.

Research Question 2: *How motion design can be based on motion capture data to improve the look of motions in DHM tools?*

It is difficult to generate natural looking motions by solely relying on mathematical algorithms. The proposed solution presented in this thesis is a motion synthesizer platform. When a motion scenario is requested, the motion is composed by putting pieces of real motions stored in the database together and a new motion based on them is synthesized. The result can be directly used in the DHM tools or can be used as a root motion to be further modified by motion generation algorithms. The functionality of the developed synthesizer platform was validated and presented in paper II.

Chapter 8. Further Research

Efficiency of the suggested platform is highly dependent on the quality and extensiveness of the annotations. For short, single, and primitive actions this can be easily handled manually but for long motion files consist of several compound actions, sophisticated algorithms shall be employed to automatically detect the actions, the engaged body segments, and the start/stop frame of an action. Number of researchers such as (Barbi, Safonova et al. 2004) has been worked on this problem but still more development is needed.

The presented solution for the storage of motion data is using a standard database management system. These systems are working optimally for normal queries such as finding values or ranges and also compound relational queries. However, when the platform is more developed, the type of queries which is needed to be handled by the database is more a pattern search and/or similarity matching type. Further studies shall be done to experiment the performance of the present database platform on new query types.

In most of the cases included paper II of this thesis where there is a need to judge a motion as natural or unnatural, visual feedback from observers is the base of decision. It is not clearly known how a human being can easily recognize if a certain motion is performed by a real human or not. Progress in the development of methods which can classify motions from the natural looking point of view, not only helps to filter out unnatural motions automatically but also can reveal key features behind the scene of human brain while motion generation.

A possible next step in using the motion synthesizer platform is to mix it with mathematical motion modelling approaches. If the same standard is followed in motion annotating by both approaches, a new motion can be generated by mixing motions which is generated from mathematical model for one part of the body (e.g. upper body) and motions taken from a database for another part (e.g. lower body). Also motions which are generated by a motion modeller can be compared and validated if a similar motion exists in the database. Finally, the synthesizer platform and the motion modeller can be cooperatively utilized to synthesize a complex action including numbers of simpler motions by mixing them from both sources. For example, more regular actions such as walking can be taken from the database and more specific actions such as assembling a part can be handled by the motion modeller.

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