



TAMPERE UNIVERSITY OF TECHNOLOGY

RIIKKA KÄSNÄNEN
MANUAL WORK EVALUATION IN VIRTUAL ENVIRONMENT
UTILIZING DIGITAL HUMAN MODEL
Master of Science Thesis

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KÄSNÄNEN, RIIKKA: Manuaalisen työn arviointi virtuaaliympäristössä

digitaalisen ihmismallin avulla

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RULA

Nykyään ergonomian arvioinnissa valmis tuote tai fyysinen prototyyppi on lähes välttämätön. Prototyypin valmistus on resursseja kuluttava prosessi, joten ergonomian arviointi jää usein vasta tuotekehityksen loppuvaiheeseen. Muutosten tekeminen muuttuu kuitenkin sitä kalliimmaksi, mitä pitemmälle prosessissa edetään, joten kehityskohteiden havaitseminen jo aiemmissa vaiheissa on huomattava etu. Virtuaalitekniikoiden avulla on mahdollista kehittää sekä tuotteista että ympäristöistä virtuaalimalleja, ja siten ottaa ergonomian arviointi osaksi tuotekehitysprosessia sen alkuvaiheessa. Tämän diplomityön tarkoitus on kehittää järjestelmä manuaalisen työn arviointiin virtuaaliympäristössä (VE) käyttäen digitaalista ihmismallia (DHM).

Tässä diplomityössä tutkitaan virtuaalitekniikoita ja systemaattisia asentoanalyysijä. Työssä kehitetään sovellus liikkeenkaappauksen perusteella ohjautuvasta ihmismallista ja siihen liitetystä automaattisesta RULA-analyysistä. Järjestelmän oikeellisuutta tutkitaan sitten käyttäjätestauksen avulla, ja sovelluksen antamia tuloksia verrataan manuaalisen RULA-analyysin tuloksiin.

Järjestelmän kehitystä ei saateta työssä kokonaan loppuun johtuen liikkeenkaappauksessa edelleen esiintyvistä vakausongelmista. Liikkeenkaappausta lukuunottamatta järjestelmä todetaan kuitenkin oikein toimivaksi. Ihmismallin vakaus onkin tärkein sovelluksen jatkokehityskohta, ja kun se saadaan toimimaan kunnolla, on järjestelmä käyttökelpoinen tulevilla projekteilla.

ABSTRACT

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Ergonomics evaluation these days almost necessarily requires a ready product or a physical prototype. Prototype manufacturing is a resource consuming process, so ergonomics evaluation often is left to latter stages of product design. However making changes gets more expensive as the process proceeds so it is a significant advantage to be able to discover the targets of alteration in earlier phases. By the use of virtual techniques it is possible to make virtual models of products and environments and thereby take ergonomics evaluation as a part of design process in it's early stages. The purpose of this Master's thesis is to create a system for manual work evaluation in a virtual environment (VE) using a digital human model (DHM).

In this thesis virtual environment technology and systematic postural analysis methods are studied. An application of a motion capture controlled DHM added with an application of automated RULA analysis is implemented. The system validity is then evaluated by user testing and the system results are compared to results of manual RULA analysis.

The development of the system is not fully finished as stability problems in motion capture still remain. However, apart from motion tracking, the system is working correctly. DHM stability is the most essential target for further development. As soon as the tracking part is gotten to work properly, the system is fit for use in future projects.

PREFACE

This Master's thesis was done at VTT Technical Research Center of Finland between January 2010 and April 2011. The author has had advise from co-workers and used pre-existing code blocks as reference material.

I would like to thank my thesis examiners assistant professor Timo Partala and team leader Kaj Helin. I'd also like to thank my colleagues for support, special thanks to Reino Ruusu for guidance in programming and mathematical problems.

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TERMS AND DEFINITIONS

| | |
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| Augmented reality | Use of e.g. transparent glasses on which a computer-generated data is displayed so that the user can view data superimposed on real-world scenes (Blade and Padgett, 2002b, p. 17). |
| Cabin of the Future, COFEX | A project at VTT aiming at creating a simulator for user experience evaluation and testing, and forming a group of generic principles and guidelines for integrating user experience in machine and industrial workplace design. |
| Cave Automatic Virtual Environment, CAVE | A display system where images are projected on walls, floor and ceiling of the space surrounding viewer (Blade and Padgett, 2002b, p. 18). |
| Digital human model, DHM | A digital representation model of a human body, often used in ergonomics simulation. |
| Ergonomics | Study of human factors , i.e., the interaction between human and their operating environment (Blade and Padgett, 2002b, p. 19). |
| Forward kinematics | A kinematics method (used especially in robotics), where the end-posture of an object is gotten by going through each joint angle. |
| Haptic | Skin-related information. Sometimes refers to information obtained by active touch and manual exploration. (Blade and Padgett, 2002b, p. 20.) |
| Head-mounted display,HMD | Headgear for viewing virtual environment. Most HMDs have also position tracking system for providing the VE system the head position and orientation data (Blade and Padgett, 2002b, p. 20). |
| Human-computer interaction, HCI | Study of how people work with computers and how computers should be designed to help efficient human operation with them (Blade and Padgett, 2002b, p. 20). |
| Inside-out beacon tracking | A tracking method where bearing sensors are attached to an object being tracked and the beacons or targets are placed in fixed locations around the tracking volume (Foxlin, 2002, p. 193). |
| Inverse kinematics | A kinematics method (used especially in robotics), where the end-posture is known and the goal is to calculate the optimal joint-values based on it. |

| | |
|---|---|
| Manual Work Support Throughout System Lifecycle by Exploiting Virtual and Augmented Reality, ManuVAR | A VTT coordinated EU project studying manual work support exploiting VR and AR. |
| Motion platform | Controlled physical system providing simulation of VE displayed motion with real motion (Blade and Padgett, 2002b, p. 21). |
| National Institute of Occupational Safety and Health Lifting Equation, NIOSH | An ergonomics evaluation method surveying lifting task safety. The method was created by <i>National Institute of Occupational Safety and Health</i> (URL: http://www.cdc.gov/niosh/). |
| Occlusion | Hiding an object or a portion of an object from sight by interposition of other objects (Blade and Padgett, 2002b, p. 21). |
| Orientation | Sense of directions, such as up and down or north and south (Blade and Padgett, 2002b, p. 22). |
| Outside-in beacon tracking | A tracking method where bearing objects are placed around capture volume, sensing targets or beacons attached to an object being tracked (Foxlon, 2002, p. 193). |
| Ovako Working Posture Analysis System, OWAS | An ergonomics evaluation method created in Finnish steel industry in 1970's. |
| Presence | Here an illusion of being present in a VE (Blade and Padgett, 2002b, p. 22). |
| Rapid Entire Body Assessment, REBA | A full-body extension of <i>RULA</i> method. |
| Rapid Upper Limb Assessment, RULA | A commonly used ergonomics evaluation method for examining worker exposure for risks inflicting work-related upper limb disorders. |
| Telepresence | Perception of being in a different location created by sensory data transmitted from that location (Blade and Padgett, 2002b, p. 23). |
| User-centered design, UCD | Design around the user needs and goals with real users involved in the design process (Blade and Padgett, 2002b, p. 25). |
| Virtual environment, VE | Three-dimensional data set describing an environment based on real-world or abstract objects and data (Blade and Padgett, 2002b, p. 26). |

| | |
|---|---|
| Virtual prototyping | Product design based on use of VE. Provides an alternative for traditional design cycle by eliminating the fabrication of physical prototypes. |
| Virtual reality, VR | Often used as a synonym to Virtual environment. In this thesis it is used as a more generic term defining the concept. |
| VTT Technical Research Center of Finland | A globally networked multitechnological contract research organization operating under the Finnish Ministry of Employment and the Economy (URL: http://www.vtt.fi) |

1. INTRODUCTION

In research and development today evaluation of ergonomics is often possible only at late stages of the process. The evaluation requires a ready product or at least a physical prototype. By bringing together the product and the user by means of virtual techniques the ergonomics aspects can be evaluated even at early design phases. This way the ergonomic goals for development can be located earlier and therefore with much lower costs.

This thesis discusses manual work evaluation in virtual environments. It focuses on motion capture with optical tracking and automatic ergonomics analysis with a digital human model (DHM). The thesis also suggests how the resulting system can be utilized in a user-centered design (UCD) process.

The target of this study is to transform motion capture data gained with optical tracking system into a virtual environment, implement a digital human model based on the motion capture and integrate certain automatic ergonomics evaluation methods into the system. In addition it targets on creating the system modular and generic.

The research problem of this thesis is how to create a system for analyzing ergonomics aspects automatically in virtual environments by means of motion capture and digital human model. The thesis will answer to the following questions. How to merge different ergonomics evaluation methods for analyzing manual work in virtual environments? Should the motion capture rather be done using inverse kinematics or forward kinematics? How to build the system in a way that it is not bound to certain tools but can be reused with different hardware and software? The system developed must be generic enough to be applied not only in known cases but also in future projects. The results of the thesis will be exploited in manual work evaluation in virtual environment.

The first step in the thesis process was to find out in this case, what is the most suitable way to carry out the motion capture. It was done by Vicon Nexus software using inverse kinematics. Next step was to find out what information needed to be transferred from Vicon to Virtools in order to implement the digital human model and ergonomics evaluation methods. After that the system was built and the results were validated with user testing.

2. BACKGROUND AND ORGANIZATION

The thesis relates to two projects of *VTT Technical Research Center of Finland*. The first project *ManuVAR (Manual Work Support Throughout System Lifecycle by Exploiting Virtual and Augmented Reality)* is a VTT coordinated and partly EU financed project that aims at developing an innovative technology platform and a framework to support manual work throughout the product lifecycle. The second project *COFEX (Cabin of the Future)* is a VTT project in which the objective is to create a simulator for user experience (UX) evaluation and testing, and to form a group of generic design principles and guidelines for integrating user experience in machine and industrial workplace design.

2.1 VTT

VTT Technical Research Centre of Finland is a globally networked multitechnological contract research organization. VTT provides high-end technology solutions and innovative services. VTT's goal is to enhance customers' competitiveness and create conditions for sustainable development, employment and wellbeing in society. (VTT, 2009.)

VTT is the biggest multitechnological applied research organization in northern Europe. It was established in 1942. It is a non-profit-making organization that operates under the Finnish Ministry of Employment and the Economy. VTT employs nearly 3000 persons and its turnover in 2010 was estimated 276 M€. (VTT, 2009.)

2.2 Previous studies

Motion capture and human models are widely noticed tools of ergonomics studies in product development in technological and medical industries. Film industry and game developers have also been important forerunners in the field of motion capture and virtual reality. In the following paragraphs a few studies in the field of ergonomics and virtual environments are introduced.

In 2008 Ma et al. examined manual assembly and maintenance work in VR and in addition to posture analysis they created a muscle fatigue and recovery model. The study used a digital human model founded on detailed mathematical calculations. They received very exact analysis data. However the analysis was not based on motion capture, but the model was manually controlled.

Mavrikios et al. (2007) also studied the use of manually controlled digital human models and posture analyses for study of manual assembly work. In the study they used the *Division MockUp 2000i2* ergonomic model and posture analysis methods were included in the model. According to the study it was found that the use of commercially available ergonomics tools integrated with VR are efficient means for ergonomics optimization.

In 2009 Li & Zhang studied coal miners' safety utilizing virtual reality technologies. They built a virtual model of a worker and the environment and produced a simulation of the workers' movement in the environment. Motion capture was not utilized in this study either, but the miner character was moved by using control keys. The study was based on Virtools and 3DMAX models.

Integrating motion capture to their study in the field of medicine, Person et al. (2001) studied high-frequency posture sampling for ergonomic assessment of laparoscopic surgery. They created an optoelectronic measuring system for high-frequency RULA analysis. The motion capture was based on the use of a basic video camera and markers attached to surgeons' hands.

Jayaram et al. (2005) also used real-time analysis features. They performed a real time VR analysis for occupational ergonomics evaluation. The study presented two viewpoints to the issue. A commercial solution Jack, was found to be a working but rigid method with its predefined functionality. On the other hand, in order to be accurate their own devised system using a single unit virtual environment would have needed more markers than were available.

3. THEORETICAL BACKGROUND

The concept of virtual reality is rather old but as technology evolves new and more comprehensive utilization potential is discovered. Virtual environments are widely used in different industries and they have huge potential in bringing human factors ever earlier and more efficiently into product, space and interface design processes. In this chapter the theory of virtual environments and ergonomics evaluation is discussed.

3.1 Virtual environments

The concept of computer-generated virtual environment (VE) was presumably first introduced by Ivan Sutherland in 1965 within his report headed "The Ultimate Display" (e.g. Blade & Padgett, 2002a, p. 1168). The terms virtual environment and virtual reality (VR) are often used as synonyms. However VE can be defined as a certain application of VR technology, consisting of certain VR elements. VR is widely utilized in commercial media such as movie and gaming industries. Yet it is also adopted as an important tool in human factors studies. It is utilized especially in context of ergonomics studies and workplace design.

Virtual environment is traditionally described as a medium consisting of a collection of hardware, including computers, head-mounted displays, headphones and motion-sensing gloves (Steuer, 1995, p. 33). Yet the technical declaration does not entirely cover the concept. An essential feature of VR is the users *presence* meaning a sensation of being in an environment (Steuer, 1995, p.34). Still presence in VR is different from a real life presence. To define the phenomenon better, the concept of *telepresence* has been derived. It means "*a sensation of being elsewhere, created by virtual reality technology*" (The Oxford Dictionary of English, 2005). In other words telepresence refers to a presence in an environment that is not concretely present, but is created by technological devices. The created environment can be either imaginary or even an accurate representation of an existing setting.

3.1.1 Virtual environment technology

As VR has developed during the past decades, also the range of technology has expanded. The technologies currently used in virtual engineering include CAVE environments, power walls, holographic workbenches, individual immersive systems, headmounted displays, tactile sensing interfaces, haptic feedback devices, multi-sensational devices, speech interfaces and mixed reality systems (Talaba et al., 2010, p.

1). The computer performance continuously increases and expands opportunities for ever wider and more complex environments and detailed visualizations. The development improves verisimilitude and enables more distinct interaction.

Computer generation of virtual environment requires a lot of physical memory, high-speed processors, high-bandwidth mass storage capacity and a high-speed interface port for input/output devices (Durlach & Mavor, 1995). In general VR technology consists of human-machine interface (HMI) devices as well as the hardware and software used to generate the virtual environment (Stanney & Zyda, 2002, p 2). Basically the HMI devices present the environment to the user, but they can also include features enabling interaction with the surroundings. In addition the system includes techniques and electromechanical systems used in design of VE systems, and also communication networks creating connection to shared virtual realities (Stanney & Zyda, 2002, p. 2). This enables the concurrent use of components attached to separate, compatible virtual environments.

3.1.2 Human-machine interface

The human-machine interfaces of VEs consist of multimodal devices representing data to the user (Stanney & Zyda, 2002, p. 2). Audio-visual devices vary and at present also haptic devices are becoming more common.

A visual mediation device could be for example a head-mounted display such as glasses or a helmet, but it can also be a virtual retinal display that reflects the picture straight to the retina by low-power RGB light (Stanney & Zyda, 2002, p. 3). Also external visual devices such as Caves and screens are widely used.

Especially when using a helmet, the auditorial devices can be attached to head gear. This way the sense of presence is often gained more profound than if the device is detached from the subject. Haptic technology provides versatile ways of adding sense of touch to VEs. Haptic gloves and other sensing devices are continuously evolved and thereby the verisimilitude is furthermore improved.

3.1.3 Ergonomics study in virtual environment

Virtual environments are utilized in the different fields of ergonomics such as work place design, user interface design, procedure testing, education and training. Virtual environments are important tools for ergonomics because of their possibilities for ergonomics studies and unique HCI issues (Wilson, 1997, p. 1060). The use of VEs enables taking ergonomics as an efficient part of product design.

In early phase visualization, virtual environments enable researchers and developers to find problems concretely in an early phase of design process when alterations are still easy to realize. VE is a potential tool for supporting different ergonomics contributions. It allows researchers and developers to test the assessment of workplace layouts from egocentric viewpoints for testing consequences for reach and access,

reconfiguring and testing alternative interface designs, checking operating and emergency procedures, training for commercial and industrial tasks as well as teaching in special needs or general sectors (Wilson, 1997, p. 1062).

Virtual prototyping on the other hand allows products or environments fast, interactive and intuitive altering and rearranging. VE can also operate as a control or communication medium. It can be utilized in rehearsal of control for planning or training purposes. (Wilson, 1997, p. 1061.)

Communication especially in training, data representation and marketing sense can also be carried out through VEs. In ideal case the communication and design can all happen in real-time and prevent collisions.

Issues concerning ergonomics studies in VEs can be divided into two categories, which are the same as in traditional ergonomics studies. The first category consists of issues related to production ergonomics and the second of issues related to product ergonomics (Wilson, 1997, p. 1061). However there are some additional issues concerning especially VE evaluation.

One usability issue related to ergonomics studies in VEs is that the guidelines developed for traditional HCI evaluation usually are not directly suited for VE evaluation. For example in a VE the user operates more intuitively within an information space than in a traditional user interface, so computer dialogue guidelines are in many respects redundant. At least in theory the interaction should not be harder or easier than in real life. Of course in practise this is not exactly the case for the use of sensors and other devices. (Wilson, 1997, p. 1073.)

Traditional ergonomics evaluation methods are systematic and therefore reasonably easy to be executed automatically in virtual environments. Yet all the method details are not easy to include in the system automatically. For example context variables are not always automatically measurable but need manual estimation and input to the system. Therefore a need for an ergonomics expert taking part in the evaluation can not be totally eliminated if precise results are required. Yet indicative results can be achieved even without ergonomics expert involvement. However the results of traditional evaluation methods are usually suggestive, so there has to be an understanding of at least ground rules of ergonomics to draw conclusions based on them.

3.2 Motion capture

A motion capture system consists of two parts; sensing and processing (Moeslund & Granum, 2001, p. 232). The sensing phase requires some kind of a tracking system.

There are two kinds of tracking systems, active and passive. In active sensing sensing devices are attached to the subject's body and the surroundings. The devices communicate with each other by signals. Passive sensing on the other hand is based

on natural signals such as visible light or magnetic wavelength and does not require wearable equipment. (Moeslund & Granum, 2001, p. 232.)

In tracking head and hands are usually the most important parts. Head tracking allows the user to view the environment from a correct perspective and hand tracking enables e.g. grabbing and touching elements of VE. According to Kalawsky (1993, p. 153), optical tracking systems are more commonly used than those based on any other techniques. Optical tracking systems are further discussed in chapter 3.2.1.

In the processing phase the tracking data is converted and processed forward to achieve a form that best suites the application needs. The processing of tracking data can either be based on inverse kinematics or forward kinematics. Whereas in forward kinematics human joint angles are used to find correct end-posture, in inverse kinematics the end-posture is known and each individual joint angle is calculated on grounds of it. Inverse kinematics is intrinsically more complex than forward kinematics for there can be a large number of different angle combinations resulting in same posture, and the inverse kinematics algorithm has to find the one with maximum speed and minimum work (Foxlin, 2002, p. 176). However the use of inverse kinematics allows to use a more simple tracking system. With inverse kinematics the whole upper body motion can be calculated with only head and hand tracking, whereas in forward kinematics also upper arm and lower arm tracking is needed separately.

In order to clarify and simplify the data they are then usually somehow visualized. Digital human models (DHM) are a common and practicable tool for visualization of human motion data. The basics of digital human models are covered in chapter 3.2.2.

3.2.1 Optical tracking

As mentioned above, optical tracking systems are the most common tracking system type. Optical tracking systems were first considered in early 1970's, but the technology was not powerful enough to track moving objects yet. By early 1980's sensoring and image processing technology was developed enough to consider optical trackers from a practical viewpoint. (Kalawsky, 1993, p. 153.)

Optical tracking systems are based on either visible light or near-infrared light and most of them use some form of bearing sensors to track pointlike targets or beacons. The most common and simple arrangement is known as *outside-in beacon tracking*. Two or more cameras are placed on the workspace and the sensors detect the direction to the targets attached to the object being tracked and the camera data is then triangulated to a 3D image by the computer. In the opposite arrangement called *inside-out tracking* the bearing sensors are attached to the object being tracked and the beacons are placed on fixed locations around the volume. (Foxlin, 2002, p. 193.)

3.2.2 Digital human models

A digital human model (DHM) is an electronic representation of a human body. Representations of human body have been studied for decades and new technologies have accelerated their use for example in computer animations, movie special effects and military battle simulations (Honglun et al., 2007, p. 351). Still comprehensive human modelling is not simple and as yet a perfect model does not exist. A model to use has to be case-specifically picked on the grounds of application needs.

Ergonomic virtual human model is one of the basic elements of ergonomics simulation (Honglun et al, 2007, p. 351). Human models are created in compliance with biomechanical and anthropometric studies. Biomechanics studies forces effecting to living organism such as human body and anthropometry examines human body structure and measures. In addition digital human models are built on grounds of a kinematic model of human motion and joint angles.

A digital human model consists of geometrical segments that are connected to each other by joints. Due to usability and efficiency factors, the skeleton structure is usually more simplified than an actual skeleton, but the measures correspond to anthropometric statistics and kinematics are based on biomechanical features (Honglun et al., 2007, p. 352). Therefore adequate accuracy is attained even though the model does not all-out equate reality.

For simplicity and clarity, in ergonomics simulation the anthropometrics based P05, P50 and P95 models are frequently used. P5 models a short person and its measures are such that only around 5% of people are shorter than the model. P50 approximates to an average height person and P95 to a tall person so that roughly 5% of people are taller than the model. There are separate anthropometric statistics for men and women and therefore also separate models for both sexes are required. This means that using anthropometrics it is efficiently possible to model the whole variety of people adequately accurately by using six different human models.

3.3 Ergonomics

The word ergonomics is a compound of a Greek words *ergos* meaning work and *nomos* meaning law. Ergonomics can be defined in many different ways. One commonly used definition is the one given by International Ergonomics Association whereby the focus on ergonomics is to understand the interaction between human actor and other elements of a system (IEA, 2000). In addition to the human the system consists among others of methods, tools, situations, locations and psychosocial factors (Pheasant & Haslegrave, 2006, p. 4). The objective in ergonomics is safety and wellbeing of people as well as maximization of system productivity.

Ergonomics examination takes into account comprehensively the physical, cognitive, social, organizational, environmental and other essential viewpoints. The field can be

divided in three fields of specialization that are physical, cognitive and organizational ergonomics (IEA, 2000). In this thesis the focus is on physical ergonomics.

Physical ergonomics investigates anatomic, anthropometric, physiological and biomechanical features of a human in action. Key subjects of physical ergonomics are working postures, materials handling, repetitive movements, work-related musculoskeletal disorders, workplace layout, safety and health. (IEA, 2000.)

Cognitive ergonomics focuses on human mental processes such as perception, memory and reasoning. Some of the key issues in cognitive ergonomics are mental workload, decision-making, human–computer interaction (HCI), stress and training. (IEA, 2000.)

Organizational ergonomics pursues the optimization of the socio-technical systems such as organizational structures, processes and policies. The central topics include communication, management, design of work and working-hours, organizational culture, remote work and quality management. (IEA, 2000.)

In ergonomics studies systematic barometers and design standards are utilized. In case of physical ergonomics the indicators are usually various posture analysis methods and other analyses that typically describe the level of ergonomics as a numeric value.

3.4 Ergonomics evaluation methods

Physical ergonomics can be evaluated for example through electrical measurement of muscle activity or by measuring posture and movement. Joint angles can also be measured with different kinds of tools and instruments. There is also a variety of aids for analyzing the measurement data by categorizing posture strain and risks related to them.

Optimization of working postures is a relevant field in physical ergonomics. Good postures promote health and safety but also productivity. Posture analysis methods usually include observation and posture estimation by eye. This leads to results being mainly indicative. Yet most of relevant issues in postures can be reliably recognized and prioritized with the analyses. In the following chapters some of the most common ergonomics analysis methods are presented.

3.4.1 Rapid Upper Limb Assessment (RULA)

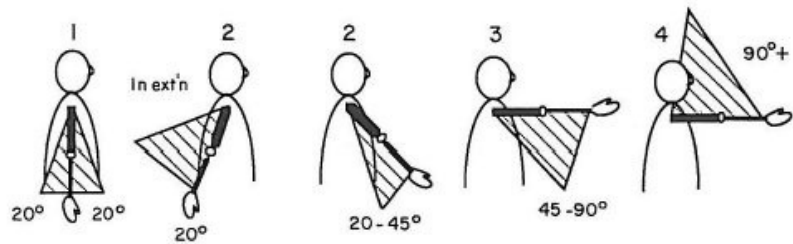
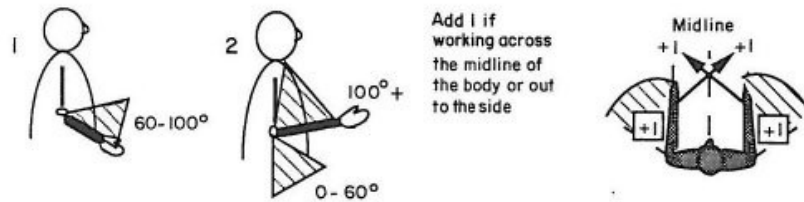
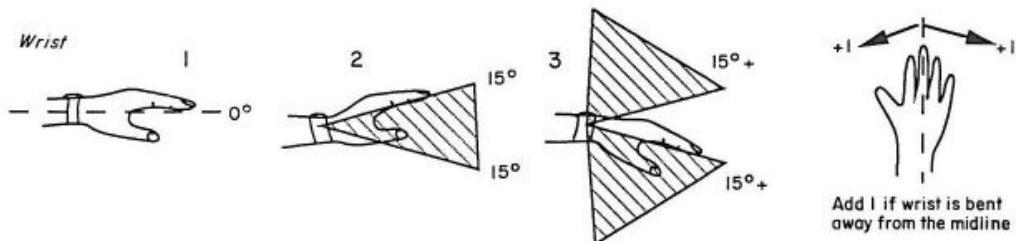
RULA (Rapid Upper Limb Assessment) is a posture analysis method for examining worker exposure for risks inflicting work-related upper limb disorders. It observes body postures, muscle exertion and workload. RULA focuses on neck, body and upper limbs.

For analysis RULA uses posture categorization and three result tables. Body postures are divided in two groups. Group A (Figure 1) consists of upper limbs containing upper arm, lower arm, wrist flexion and rotation. Group B (Figure 2) is composed of neck, torso and legs. (McAtamney & Corlett, 1993, p. 92-93.)

Upper arms

Add 1 if shoulder is raised
Add 1 if upper arm is abducted

Subtract 1 if leaning or supporting the weight of the arm

*Lower arms**Wrist**Wrist twist*

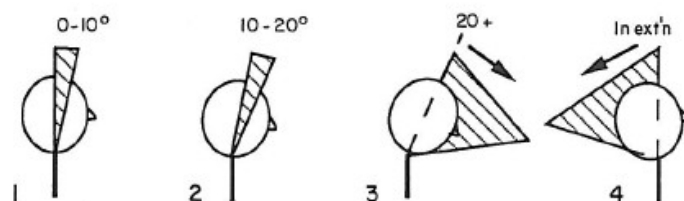
1 Mainly in mid-range of twist

2 At or near the end of twisting range

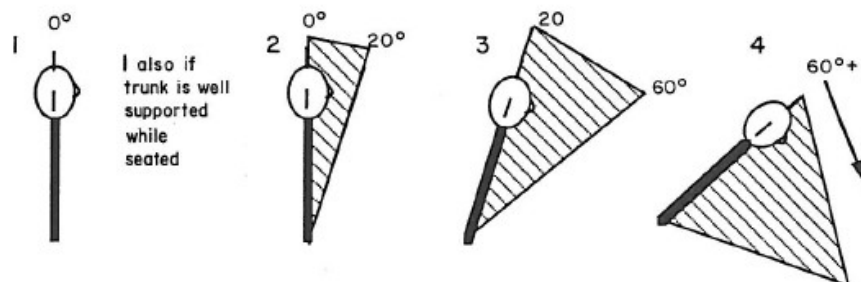
Figure 1: Group A strain scores (McAtamney & Corlett, 1993, p. 93).

Neck

Add 1 if the neck is twisting
Add 1 if neck is side-bending

*Trunk*

Add 1 if trunk is twisting
Add 1 if trunk is side-bending

*Legs*

1 if legs and feet are well supported and in an evenly balanced posture

2 if not

Figure 2: Group B strain scores (McAtamney & Corlett, 1993, p. 94).

Joint angles and muscle use are estimated and postures are scored according to them. The observation can be done live on the spot or the working process can be videotaped and analyzed afterwards. By analyzing from tape more accurate data may be achieved, because the tape can be paused for closer inspection. All the postures are usually not analyzed. The postures kept for a long time or containing large strain are identified for analysis by observing work cycles.

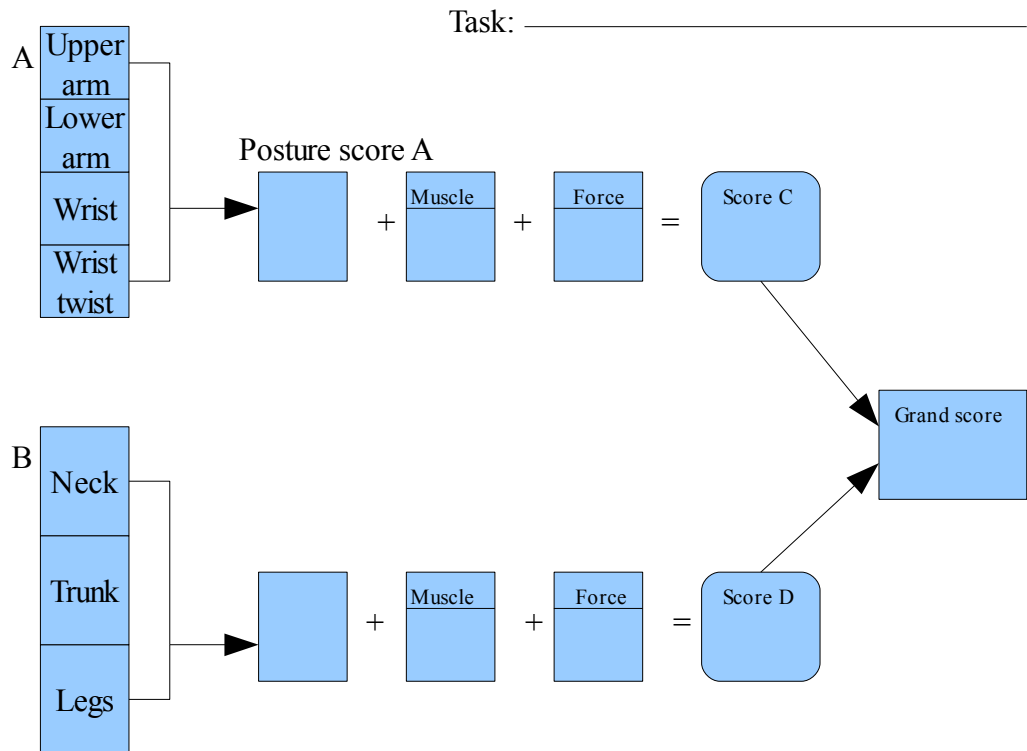
The posture group scores are determined by scores of each individual segment and joint angle in the group. The scores are collected according to the tables A (Table 1) and B (Table 2) that define total scores representing posture strain. The scores are called *value A* and *value B*. Then the total scores are collected to a summary table (Figure 3).

Table 1: RULA group A (upper limbs) aggregate score.

| Upper arm | Lower arm | Wrist alignment score | | | | | | | |
|-----------|-----------|-----------------------|---|-------------|---|-------------|---|-------------|---|
| | | 1 | | 2 | | 3 | | 4 | |
| | | Wrist twist | | Wrist twist | | Wrist twist | | Wrist twist | |
| | | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| 1 | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 3 | 3 |
| | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 |
| | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 |
| 2 | 1 | 2 | 3 | 3 | 3 | 3 | 4 | 4 | 4 |
| | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 |
| | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 |
| 3 | 1 | 3 | 3 | 4 | 4 | 4 | 4 | 5 | 5 |
| | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 |
| | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| 4 | 1 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| | 2 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 |
| 5 | 1 | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 7 |
| | 2 | 5 | 6 | 6 | 6 | 6 | 7 | 7 | 7 |
| | 3 | 6 | 6 | 6 | 7 | 7 | 7 | 7 | 8 |
| 6 | 1 | 7 | 7 | 7 | 7 | 7 | 8 | 8 | 9 |
| | 2 | 8 | 8 | 8 | 8 | 8 | 9 | 9 | 9 |
| | 3 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |

Table 2: RULA group B (body and legs) aggregate score.

| Neck score | Body alignment score | | | | | |
|------------|----------------------|---|------|---|------|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| | Legs | | Legs | | Legs | |
| | 1 | 2 | 1 | 2 | 1 | 2 |
| 1 | 1 | 3 | 2 | 3 | 3 | 4 |
| 2 | 2 | 3 | 2 | 3 | 4 | 5 |
| 3 | 3 | 3 | 3 | 4 | 4 | 5 |
| 4 | 5 | 5 | 5 | 6 | 6 | 7 |
| 5 | 7 | 7 | 7 | 7 | 7 | 8 |
| 6 | 8 | 8 | 8 | 8 | 8 | 9 |

**Figure 3: RULA summary table.**

In addition to joint values also the muscle use and load are taken into account separately for groups A and B. Load values C and D are counted by adding muscle and force scores to the values A and B. The final result is found in a result table based on values C and D. The result score varies from one to seven and defines a value for a need of actions stage (Table 3).

Table 3: Level of actions is derived according to values C and D.

| | | Value D (Neck, trunk, legs) | | | | | | | | |
|--------------------------|---|-----------------------------|---|---|---|---|---|---|---|---|
| Value C (upper limbs) | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| | 1 | 1 | 2 | 3 | 3 | 4 | 5 | 5 | 5 | 5 |
| | 2 | 2 | 2 | 3 | 4 | 4 | 5 | 5 | 5 | 5 |
| | 3 | 3 | 3 | 3 | 4 | 4 | 5 | 6 | 6 | 6 |
| | 4 | 3 | 3 | 3 | 4 | 5 | 6 | 6 | 6 | 6 |
| | 5 | 4 | 4 | 4 | 5 | 6 | 7 | 7 | 7 | 7 |
| | 6 | 4 | 4 | 5 | 6 | 6 | 7 | 7 | 7 | 7 |
| | 7 | 5 | 5 | 6 | 6 | 7 | 7 | 7 | 7 | 7 |
| | 8 | 5 | 5 | 6 | 7 | 7 | 7 | 7 | 7 | 7 |
| | 9 | 5 | 5 | 6 | 7 | 7 | 7 | 7 | 7 | 7 |

Need of actions value divides in four stages according to the result and defines how critically the posture needs to be evolved and examined further. The stages are signified as follows:

- Stage 1 (score 1-2)
 - Posture is acceptable on condition that it is not held for long or repeated often.
- Stage 2 (score 3-4)
 - Further study required and alterations possible.
- Stage 3 (score 5-6)
 - Further study required and alterations must be done soon.
- Stage 4 (score 7)
 - Further study required and alterations must be done immediately.

The goal in the development of RULA was to create a method that would be quick to use and would not need any equipment besides paper and pen (McAtamney & Corlett, 1993, p. 92). The automation of the method hinders the achievement of the latter for that execution of computer-aided posture analysis requires a complex tracking system and software. Yet the benefits achieved in resource usage are often considered to compensate the need of more complex equipment.. Through automation the time spent in note taking is saved and also the observation span can be significantly shortened producing a bigger amount of data and more accurate results. With motion capture the joint values can be measured more punctually but since the method was initially created for human observation the added value of more specific measurements is questionable.

RULA by itself is not enough to get strict values or unambiguous solutions but conclusion making requires wider evaluation and ergonomics know-how (McAtamney & Corlett, 1993, p. 98). Yet RULA is a quick and simple method for finding out the most important targets for development cost-efficiently. In the evaluation process the complexity of human being and the individual features of the surveyor and the subject of evaluation need to be taken into account (McAtamney & Corlett, 1993, p. 98). The design of alterations has to be based on ergonomics expertise and not only results of RULA.

3.4.2 Rapid Entire Body Assessment (REBA)

REBA (Rapid Entire Body Assessment) is a method expanded from RULA. When RULA centralizes on upper limbs, REBA is extended to cover the whole body. The method was created especially to answer the need of a system to examine unpredictable working postures in health care services (Hignett & McAtamney, 2000, p. 201). The operating principles in REBA equate to those of RULA. The critical aspects of a task are reviewed by assigning posture variables for each task.

As in RULA, the body segments divide in two groups. Group A consists of trunk, neck and legs whereas group B contains upper arms, lower arms and wrists. However in REBA the posture categorization is more detailed. For example in group A there are altogether 60 different posture combinations classified for trunk, neck and legs. In REBA as well as in RULA the posture variables are determined by tables and then aggregated with muscle load and force variables to calculate the final score. Final REBA scores divide in 15 stages defining the health risks and need of actions to minimize them (Hignett & McAtamney, 2000, p. 203).

3.4.3 Ovako Working Posture Analysis System (OWAS)

OWAS (Ovako Working Posture Analysis System) is a well-defined, quantitative method for posture analysis. The method was created in Finnish steel industry but it is also widely used abroad (Chaffin et al., 1999, p. 302). OWAS is suited especially for examination of task requiring whole body motion. It is not feasible in analyzing stationary tasks.

Like previously discussed methods, also OWAS utilizes posture classification added by muscle use, load and forces. Accurate posture classification divides the back postures in four, upper limb posture in three and lower limb postures in seven different classes on top of three classes of object weight or muscle usage (Suurnäkki, 1987, p. 23). The postures are visually estimated either using direct observation in context of work or from video recording. By choice the subject is viewed from one or both sides and observation is done with systematic sampling. In context the ideal sampling rate is every 30 - 60 seconds and from video every 5 – 15 seconds (Louhevaara & Suurnäkki, 1991, p. 6). The ideal sampling rate is higher with a recording because a video can be paused

during analysis. Hence it is possible to analyze bigger amount of postures from video than it is in context, which leads to more accurate results. In systematic sampling the considered postures are based on timing. Due to sampling rate, some poor postures may fail to be noticed. On the other hand if the sampling rate is cautiously chosen, the posture is not likely to occur frequently or be held for long.

In the posture classification phase of OWAS, each posture constitutes a four-figure key value. In addition to posture variables, it is also well advised to take some task variables into consideration. The posture keys can be stored in *WinOWAS* software which can also be used in the analysis phase to for example print out posture frequencies or level of action distributions. There are also other computer software to support the OWAS process. For example *OWASCA* tutorial program can be used in learning the method. (Louhevaara & Suurnäkki, 1991, p. 11.)

In OWAS as well as previously introduced methods, the resulting value specifies a level of actions needed to correct the posture. In OWAS there are four different levels. The first level expresses that no actions are needed and the fourth level means that severe actions are needed immediately.

One of the benefits of OWAS comparing to other methods is its repeatability between separate observers. The repeatability has been field-tested in a dozen different industries tasks and discovered that an average of 93 % of observations were same for different observers (Louhevaara & Suurnäkki, 1991, p. 7). A downside of OWAS is that the classification of upper limb postures is not very accurate compared to for example RULA. Considering efficiency, the supportive software can then again be considered as a remarkable benefit.

3.4.4 NIOSH Lifting Equation

Lifting tasks are often the cause of serious musculoskeletal disability (Chaffin et al., 1999, p. 292). Therefore it is particularly important to study the safety of lifting tasks extra carefully. *NIOSH* (*National Institute of Occupational Safety and Health*) lifting equation, named after the developer organization, is a method studying central factors of lifting work strain. With the equation a set of guidelines are defined for common lifts. It considers the lifting duration and frequency. At some cases the equation may misestimate the strain and more specific ergonomic studies are then needed to evaluate other physical stress factors.

There are certain limitations on the task for the NIOSH equation to be valid. It is for example not suitable if the lift is done with one hand, for unstable load or on a slippery ground. It is also not suited for tasks including pulling, pushing, or using an aiding instrument on a lift. In addition unfavorable circumstances such as temperature notably lower than 19°C or higher than 26°C as well as moisture under 35 % or over 50 % reduces the equations suitability for analysis. Swift lifts or task of duration over eight hours are not suitable for analysis with NIOSH. (Waters et al., 1994, p. 10.)

With the NIOSH lifting equation a *Recommended weight limit (RWL)* is calculated. A RWL declares the mass of load that almost every healthy person in defined conditions for a reasonable duration can lift without an increased risk of lifting related back injury (Waters et al., 1994, p. 4). In optimal conditions RWL equals 23 kg. This mass is called a *Load constant (LC)* (Waters et al., 1994, p. 115). The load constant is the biggest result RWL can have - all the factors lowering the conditions also reduce the RWL value.

$$RWL = LC * HM * VM * DM * AM * FM * CM \quad (1)$$

Recommended weight limit (1) is the product of factors effecting on a lift. In formula (1)

- LC = Load Constant
- HM = Horizontal Multiplier
- VM = Vertical Multiplier
- DM = Distance Multiplier
- AM = Asymmetric Multiplier
- FM = Frequency Multiplier
- CM = Coupling Multiplier (Waters et al., 1994, p. 113 – 117).

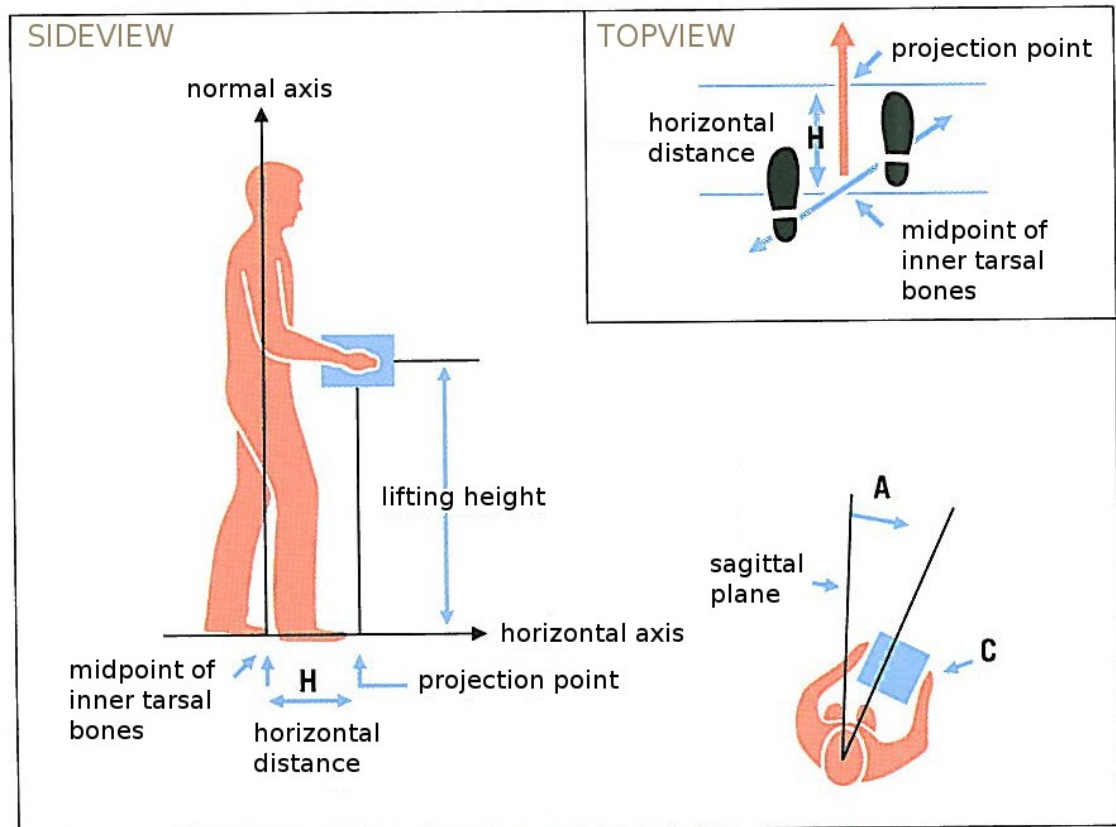


Figure 4: Factors effecting recommended weight limit (RWL) of a lift (Translated from Väyrynen et al., 2004, p. 166).

Factors of RWL are illustrated in Figure 4. The multipliers in addition to their factors and equations are introduced in Table 4.

Table 4: Introduction of the composition of multipliers and their equations.

| Multiplier | Composition | Equation |
|----------------------------|--|--|
| Horizontal multiplier (HM) | Composed of horizontal distance (H) from midpoint of inner tarsal bones to the projection point of knuckles. | $HM = 25/H$ |
| Vertical multiplier (VM) | Vertical distance (V) (in previous figure called the lifting height) is measured vertically from standing plane to the midpoint of middle fingers. The optimal lifting height is 75 cm, which is the knuckleheight of an average worker. | $VM = 1 - (0,003 * V - 75)$ |
| Distance multiplier (DM) | Distance (D) is the height difference between start point (V1) and end point (V2) of the lift. | Elevation: $D = V2 - V1$ Loweration: $D = V1 - V2$ $DM = 0,82 + (4,5 / D)$ |

| | | |
|----------------------------|---|--|
| Asymmetric multiplier (AM) | The lift is considered asymmetric when it starts or ends outside of the sagittal plane in front of the subject. Asymmetric angle (A) is measured from the strats point of the lift. | $0 < A < 135$ degrees |
| Frequency multiplier (FM) | Determined by three factors: frequency of the lift, time consumed on the lifting task and lifting height. Frequency of the lift (F) is the average value of lift per minute during 15 minutes period. If workers do not usually pursue the lifting task continuously for 15 minutes time, F is determined as follows: 1. Number of lifts per 15 minutes 2. Total amount of lifts / 15 | Usually $0,2 < F < 15$ lifts/minute |
| Coupling multiplier (CM) | Grasp between hand and object is estimated as good, moderate or bad. In estimation the whole lift needs to be considered for the grasp can vary during the lift. | CM is determined from a specific table according to the vertical position of the weight. |

$$LI = \frac{L}{RWL} \quad (2)$$

In the *Lifting Index* (LI) formula (2) L is the load mass and RWL is the recommended weight limit (Waters et al., 1994, p. 115). LI declares the relation between weight of the load and RWL in specific lifting conditions.

Individual factors of NIOSH are used for identifying certain issues concerning lifting tasks. Recommended weight limit on the other hand is used in evolving existing lifting tasks and designing new ones. Lifting index defines the relative strain of lifts. The bigger the value, the bigger percentage of workers are not able to perform the lift safely. Therefore the LI is suited for prioritizing in ergonomics development work by putting in order of importance the tasks suspected dangerous. (Väyrynen et al., 2004, p. 165 – 172.)

4. RESEARCH METHODS AND MATERIAL

This chapter discusses the research methods and material used. First the VTT virtual environment system is introduced. The VR system is used to run the case-specifically constructed virtual environment. Then the ergonomics analysis system according to the motion capture and digital human model is built in a way that it can be implemented inside each individual virtual environment built, controlled and run inside the VR system.

In chapter 4.2 the motion capture methods are discussed. The tracking part is done in Vicon Nexus and the data handling and visualization in 3DVIA Virtools software. Next the ergonomics analysis methods are covered in chapter 4.3. Some of the most used systematic methods of ergonomics analysis previously introduced in chapter 3.4 are compared and the used method RULA and its implementation are discussed more thoroughly. Finally in chapter 4.4 the system validation methods are introduced. The validation is done by user testing. In the chapter the test cases and data analysis methods are presented.

4.1 VTT virtual environment system

A virtual environment system consists of a combination of hardware and software. At VTT the basic hardware includes three data projectors, three rear projection screens and several PC's for system operation. The 3D sensation is created through stereoscopy so the hardware also includes stereoscopic glasses. Virtual environments are generated in 3DVIA Virtools software. To enhance authenticity and user experience there are for example haptic devices and a motion platform implementable to the system.

In purpose of interaction between user and the system a tracking system is required. In VTT virtual laboratory the tracking functions through eight Vicon MX cameras positioned around a capture volume and two separate software. The infrared cameras track luminous markers in the capture volume and send 2D tracking information to operating PC through Ethernet. The software then reconstructs 3D data out of the 2D tracking images.

As mentioned above, there are two separate tracking software. Vicon Tracker is used for tracking solid individual objects. Vicon Nexus on the other hand is developed for whole body tracking and is capable to create a human body model out of marker relations. The model is created based on a predefined marker set. Anthropometrical

measurements on the subject can be used to build more accurate skeleton model. Nexus has couple of predefined plug-in gait models that use a marker set and subject measurements to calculate joint midpoints that prevent the system from giving more accurate joint values.

4.2 Methods of motion capture

As mentioned above, the software used for motion capture are Vicon Nexus and 3DVIA Virtools. The hardware consists of nine infrared cameras around the capture volume and two PC's running the software.

4.2.1 Optical tracking in Vicon Nexus

Vicon Nexus handles the optical tracking part. Tracking is done for a subject wearing a tracking suit and moving on the capture volume. The suit has small reflector markers attached on it. Nexus uses Vicon Plug-in Gait Version 2.0 model that uses a predefined marker set and a set of subject measurements to create 3D data of joint kinematics and kinetics of the subject under contemplation (Vicon Motion Systems Ltd., 2010). The most efficient way would be attaching the markers straight to the subject's skin, but due to user comfort this is not easy to achieve, for it would require the user to be wearing very little clothing. Therefore a specific tracking suit is used.

The markers on the tracking suit are placed according to the Vicon Plug-in Gait marker set on the joints and other critical points seen in figures 5-10. The cameras spot the markers on the volume and the 3D data are constructed on the grounds of the 2D tracking data of each camera.

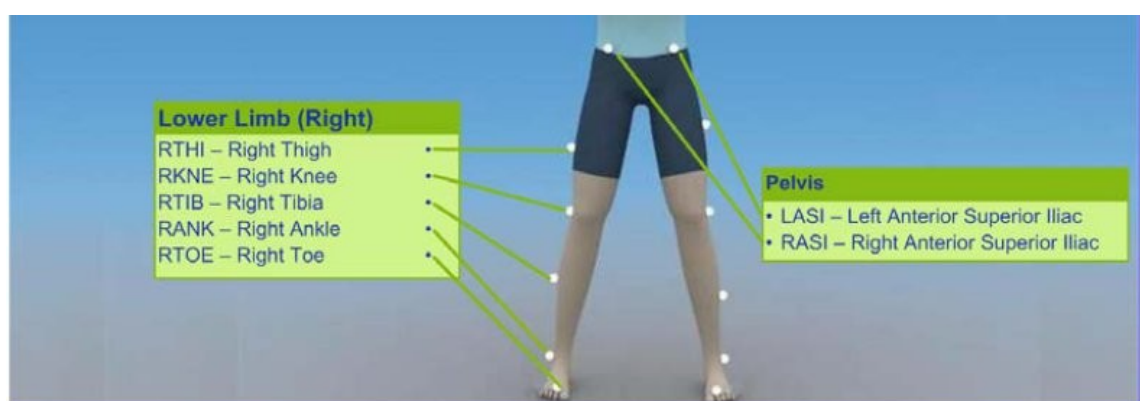


Figure 5: Frontview of marker placement for lower body (Vicon Motion Systems Ltd., 2010, p. 11).

Figure 5 illustrates the placement of markers on lower body. To avoid occlusion the markers on lower limbs are placed on sides of thighs and legs.

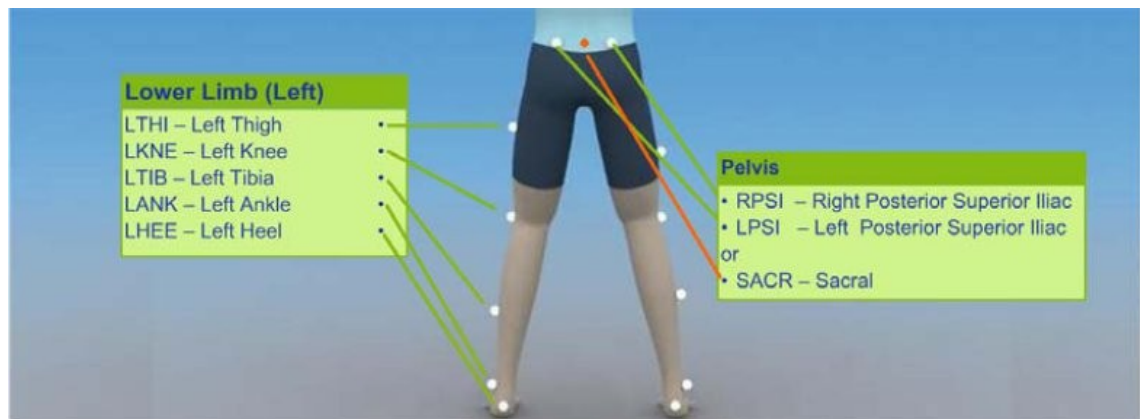


Figure 6: Backview of marker placement for lower body (Vicon Motion Systems Ltd., 2010, p. 12).

Figure 6 presents a backview of the marker arrangement on lower body. The sacral marker marked with red color is optional and used only with specific Plug-in gaits.



Figure 7: Sideview of marker placement for lower body (Vicon Motion Systems Ltd., 2010, p. 12).

In Figure 7 the sideview of lower body marker set can be seen. The markers on the left side are placed in same order but avoiding symmetry between sides. This is done by placing markers on thighs and legs assymmetrically.

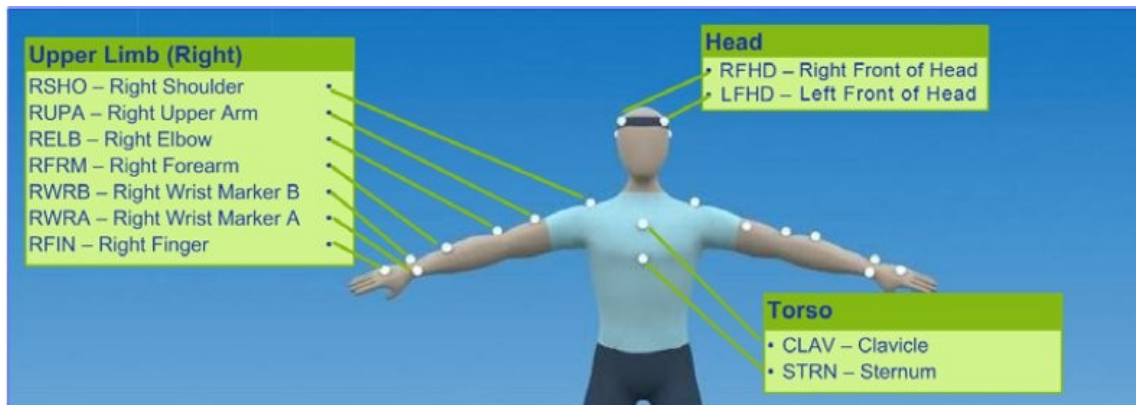


Figure 8: Frontview of marker placement for upper body (Vicon Motion Systems Ltd., 2010, p. 19).

In Figure 8 a frontview of the marker placement on upper body is presented. On upper body the markers on joints are also placed as precisely as possible and asymmetry on hands is carried out by placement of markers on upper and lower arms and hands.

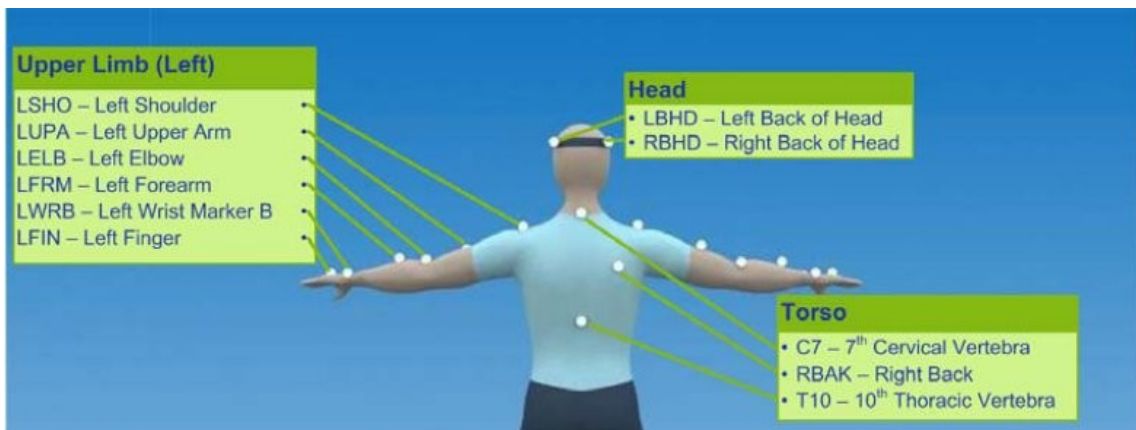


Figure 9: Backview of marker placement for upper body (Vicon Motion Systems Ltd., 2010, p. 20).

Figure 9 illustrates a backview of upper body marker set. Markers on torso are placed on correct vertebrae of the spine and one on right side of the back.

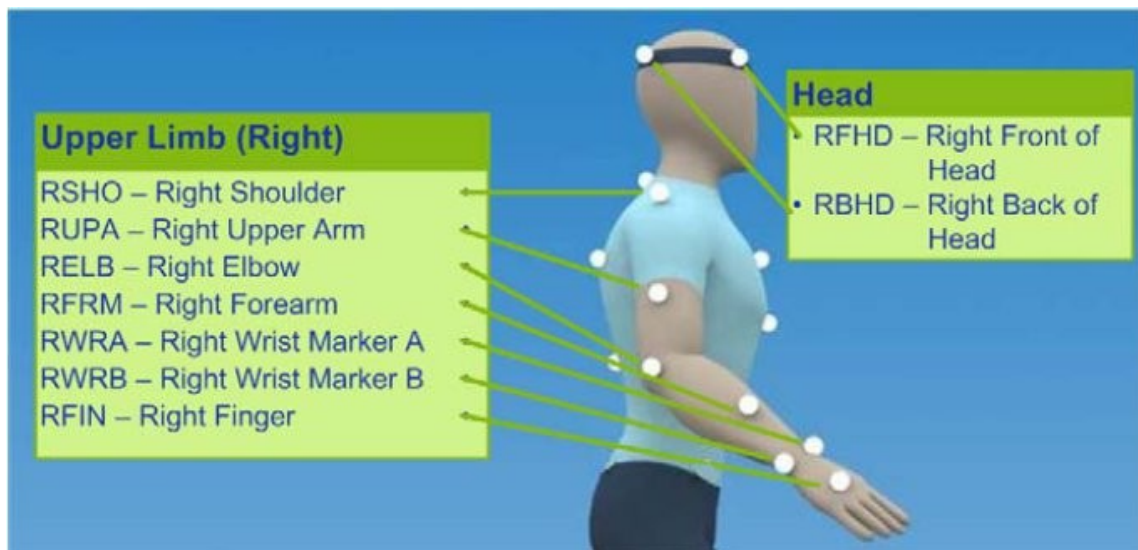


Figure 10: Sideview of marker placement for upper body (Vicon Motion Systems Ltd., 2010, p. 20).

In Figure 10 a sideview of upper body marker set is shown. The left side markers are positioned likewise, but again avoiding symmetry between arms.

When the subject measurements are entered to Nexus and the subject is wearing the suit and has placed him/herself on the capture volume, the markers need to be identified in Nexus, which then builds the dynamic model. When the model is ready, the tracking data needs to be streamed into Virtools for data handling and visualization.

4.2.2 Tracking data handling and visualization in 3DVIA Virtools

The data handling and visualization is done in 3DVIA Virtools, where also the VR is built and run. For data streaming a set of special-purpose Virtools building blocks (BBs) is needed. The BBs are constructed with Virtools software development kit (SDK) in Visual C++ language. The Visual Studio 2005 software was used for programming and debugging.

From Vicon a set of building blocks was received to realize the datastream connection between Nexus and Virtools 4.0. However the Virtools version used at VTT is 5.0, so the BBs' functioning on the current version could not be assured. Access to the BB sets source code was not gained, so building blocks with the same functionality needed to be created. The implementation carried out exploiting Vicon DataStream SDK that holds a set of functions to make the connection and gain access to tracking data.

The original BB set includes a set of BBs to stream individual markers to Virtools. However the streaming of each individual marker is inefficient and because they are not particularly needed for motion data visualization they are left out of the system.

An important issue on data streaming between the two software is that the axis system in Vicon Nexus is right-handed and in Virtools left-handed. This leads into incorrect segment orientations, so the orientation matrices need to be converted from right-handed axis system to left-handed. This is included to the *GetSegmentOrientation* building block's inner logic and the BB's resulting orientation is already converted to a correct axis system.

The sceleton fitting from Vicon Nexus segments to DHM segments in Virtools is done by transforming the coordination system and modifying the DHM segments' local coordinations.

The axis system transformation is done by matrix multiplication with certain transformation matrices.

$$M = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad (3)$$

The conversion matrix M used in handedness conversion is shown in equation 3. It represents that the change of handedness is done by swapping the y-axis and z-axis.

$$x' = M \cdot x \quad (4)$$

Equation 4 shows that an input right-handed position vector x from Vicon Nexus is transformed by a conversion matrix M to an corresponding output left-handed position vector x' in Virtools.

$$y = T \cdot x \quad (5)$$

$$y' = M \cdot y \quad (6)$$

Equations 5 and 6 show that rotated position vector y from Vicon Nexus is gotten by multiplying position vector x by transformation matrix T and the corresponding matrix y' in Virtools is gotten by multiplying the vector y by M .

$$y' = T' \cdot x' \quad (7)$$

Next the transformation matrix T' that applies the equation 7 needs to be found. In other words, by which matrix we need to multiply the position vector x' to get the rotated position vector y' in Virtools.

$$M \cdot y = T' \cdot M \cdot x \quad (8)$$

$$y = M^{-1} \cdot T' \cdot M \cdot x \quad (9)$$

$$T = M^{-1} \cdot T' \cdot M \wedge T' = M \cdot T \cdot M^{-1} \quad (10)$$

In equation 8 a substitution of equations 4 and 6 to equation 8 is done. By finding y we get equation 9 which leads to a form represented in equation 10. It shows that the left-handed transformation matrix T' is gotten by multiplying the conversion matrix M by transformation matrix T and furthermore by inversion matrix of M .

$$T' = M \cdot T \cdot M \quad (11)$$

For M is its own inversion matrix, the final form is the one shown in equation 11. The transformation can be done simply by replacing rows 2 and 3 and columns 2 and 3 of the rotation matrix.

After conversion from right-handed to left-handed coordination system, there remains one problem to solve in the skeleton fitting. To get the segments move correspondingly, the local coordination systems of segments in Vicon and Virtools need to be modified. This is done manually by comparing the local axis systems in Vicon with the corresponding segments local axis system in the DHM. If the Dir and Up vectors do not match after conversion to left-handed coordination system, they need to be reset. This is done by assigning correct *Local Dir* and *Local Up* values to a control array relating to the DHM. These values will be set into action dynamically during run time.

The DHM is located as a character inside Virtools and it is controlled through variables set in a control array. The DHM used in the system is Delmia Human, but it can be switched to any other human model that has corresponding bodyparts to those streamed from Vicon, as separate objects. In the beginning of each system run new objects for Vicon segments are created and placed in a table in the order they are streamed in from Nexus. When the run ends, the objects are deleted. The DHM segment objects are placed in a different table in the same order as the Vicon segments and the DHM is controlled by going through each table and copying the orientation from Vicon segments to those of the DHM.

The DHM is not scaled according to the subject. There are six different model for male and female P05, P50 and P95 persons. The model needs to be manually implemented according to the subject's estimated height. The models are included in six different .nmo-files that also include the table of bodyparts and a 2D screen for calibrating the models global position so that the feet are actually on the same level as the ground and the 2D screen can be set to follow the ground to get the DHM move on correct vertical position.

4.3 Methods of ergonomics analysis

Some of the common systematic ergonomics evaluation methods were introduced in chapter 3.4. The applicability of the methods for automated analysis in virtual environment was studied by the author Käsänen in her Bachelor of Science thesis (Käsänen, 2010). In the thesis certain selected features of each method (RULA, REBA, OWAS, NIOSH) were reviewed and compared to each other. In addition the thesis carried out a data analysis of interview data collected beforehand in ManuVAR project. The aim in data analysis was to find out typical features of workflows in ManuVAR partners to find out which methods would best suit the needs of these organizations. The results suggested that the most suitable analysis methods for automated ergonomics analysis in organizations participating in ManuVAR consortium were RULA and OWAS (Käsänen, 2010, p. 18). Yet because of limited time resources only one method had to be chosen for implementation in this stage.

For its simplicity and prevalency, RULA was selected to be implemented in the system. The implementation was done by constructing a special Virtools building block for RULA analysis using the Virtools software development kit (SDK). The RULA BB was constructed according to realization logics found in source codes of an existing analysis system formerly used at VTT. Yet plenty of modifications were needed for example in joint value handling.

In Virtools the system logic is carried out by connecting building blocks to each other from their input and output pins in suitable order. Required parameters are connected to the input parameter pins and resulting parameters can be received from the output parameter pins. The RULA building block was manually programmed with help of Virtools SDK.

The structure of the RULA BB is illustrated in Figure 11. In the figure the pins on sides of the block are its functional inputs and outputs, that portrays from where and where to the execution proceeds. The input pin on left side activates execution of RULA method and the output pins on right hand side represent the result of the method, in this case success (*Out* output) or failure (*Error* output).

The pins on the top of the block represent the parameters required. In this case two parameters, the character object (i.e. the DHM object) and a file name, are needed. Through this connection the joint angles are read by the analysis method straight from the character object. The output parameter pins are located on the bottom of the block. As output parameters the RULA method gives the RULA final value (*RULAv* output parameter) and in case of error a customized error message (*Error* output parameter). If an error occurs during the analysis, the *Error* output activates, otherwise the execution proceeds through *Out* output.

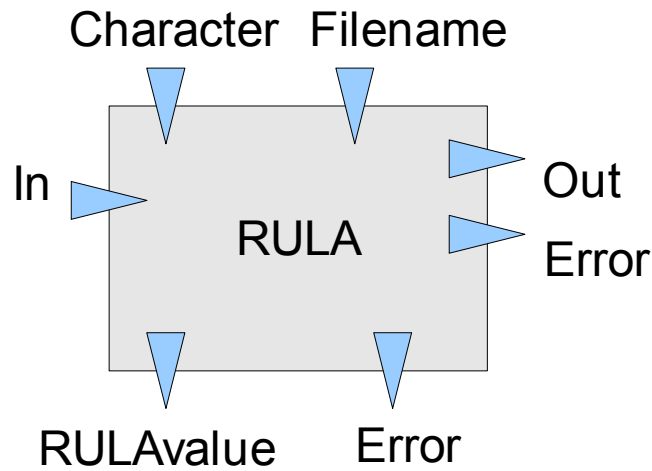


Figure 11: Inputs, outputs and parameters of Virtools building block that manages the RULA analysis.

For quick analysis, a traffic light color-coded RULA value is included in the top left corner of the systems graphical user interface. The value shows a real time RULA value that is color-coded based on its value representing the level of actions needed to correct the posture. High values representing bad postures are shown in red, median values in yellow and low values in green color. By monitoring the color bad postures can be detected easily and in real time by users with any level of experience in ergonomics.

For a more specific analysis the final value and fifteen provisional values are written in text file every 10 ms. For the analysis the data can be imported for example to MS Excel where they can be used for drawing graphical illustrations. A *tabulator* is used as a separator character in the text file.

REBA, OWAS or other methods based on joint angles are easy to be implemented later on using the same implementation principles that are used in implementation of RULA. The system administers relay of joint values from Vicon Nexus to Virtools. The connection is implemented with Vicon's and Virtools' Software Development Kits (SDKs). In Virtools a RULA building block was constructed that executes the RULA analysis based on DHM joint values. The interpretation of joint values can be found from source codes of RULA building block and so the same logic can be used in the implementation of other analysis methods.

4.4 Validation methods

The system was validated by carrying out empirical user testing. User testing aimed at finding the weak spots of the system. The focus was on finding out whether the auto-

mated evaluation results correlate to the results of manual evaluation, and does the automated system find more black spots through its higher sample rate.

4.4.1 User testing methods

The user testing took place in August 2010 and it consisted of seven test cases. Because the focus was not on the task in hand but rather the system validity, the test users did not need to be experts on the task. In fact the task was not a real life example, but an imaginary test task drawn up for the specific use.

There were seven test users in age range 26 – 37. The test took place in the middle of a holiday season, so due to the difficulties related to finding test participants, also the author of this thesis participated in the testing. This was not considered a problem for the focus in the testing was not in the system design but in testing of technical factors. In this test case the moderator was Kaj Helin, one of two thesis examiners. In the rest of the test cases the moderator was Riikka Käsnänen.



Figure 12: User testing included a manual assembly task.

The participants in the test cases were the test user and the moderator. The role of moderator in the testing was to present the test progression and the test task to the user. Though the baseline for comparison was a manual evaluation of the task, there was not

an actual human evaluator present in the situation. The test was videotaped and the evaluation was made afterwards by Käsänen according to the video.

The test case consisted of a personal data inquiry, a manual assembly task (Figure 12) and at the end an interview. The inquiry collected personal data to be used in data analysis. The test task was to assemble ten ballpoint pens and pack them in a cardboard box with some padding. The work phases were predefined to make the test cases more comparable with each other. Duration of a test case was around 30 minutes. Before the first test case a small-scale pilot testing took place that validated the test configuration and duration.

Postures to be evaluated in the manual evaluation were selected beforehand and were the same ones in each test case:

- Reaching for an empty crate from lower shelf
- reaching for crate stuffing from left hand side
- picking up a part from right hand box
- picking up the cap from the front
- screwing the cap on
- picking up a part from front left
- closing the crate and
- lifting full crate to top shelf.

There was also an option to choose additional bad postures for evaluation if any occurred. The manual RULA was performed based on video recordings and the exact time of posture occurrence was documented. Then the manual score was compared to the value in the automatic data at the same point in time. In comparison had to be taken into account that due to stability issues in motion capture all the segments did not precisely meet the reality (Figure 13) which affected automatic analysis results.



Figure 13: Motion capture data from the manual task was sent to the virtual environment, where they controlled a digital human model. Due to stability issues in motion capture the models segments did not precisely meet the reality.

The difference between manual and automated scoring was used as a validity measure. In the testing the bad postures were identified both manually and automatically. The aim was to find out if the automatic evaluation finds more or different bad postures than the human observer. However it has to be taken into account that the human observer was not an experienced RULA operator.

4.4.2 Data analysis methods

A manual RULA analysis was carried out on the basis of the video recorded during the test cases. The postures to be analysed were selected in advance and the correct points of time were then identified from each recording. For each test case 15 provisional scores of analysis of different body parts in addition to the final result were written down to an Excel file. In data analysis when disparities between manual and automatic data were found, the provisional scores were used for detecting which body parts were possibly causing error in the final score.

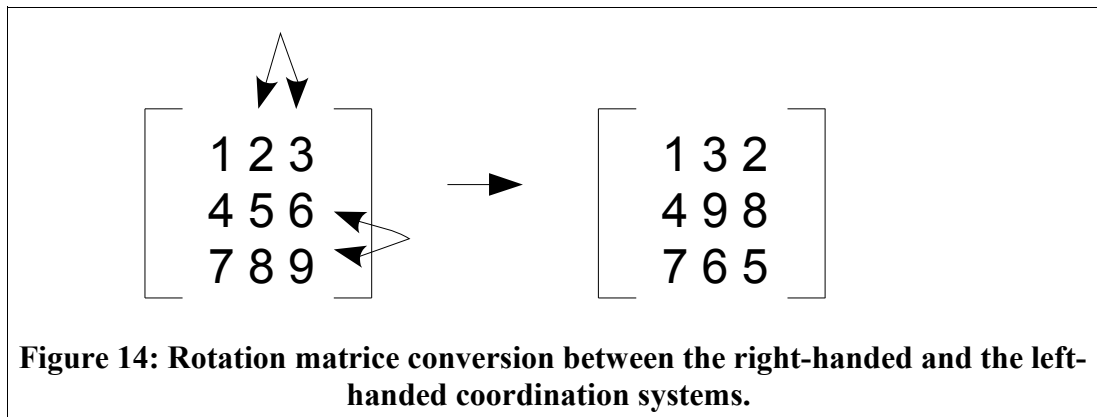
During run time Virtools recorded an .avi file of the screen view. The same posture identification as on video was then done for the animation. The animation file contains the timeline of the analysis and the correct spots in automated RULA result files were found by converting the timeline to seconds. The values in the result file were then compared to the ones gotten in the manual analysis of the same computational instant.

It could be seen in the animation which body parts were correctly oriented and which were not. This allowed to take into account the inflict that the posture flaws set on the RULA scores in the comparison. During the data analysis other observations considering the testing were also marked down and inferences were made based on them.

5. PROBLEMS AND DECISIONS

The first research problem was to find out whether to use the inverse kinematics or the forward kinematics approach. In inverse kinematics the postures are known and by them the angles are calculated, whereas in forward kinematics the angles are known and by them the postures are solved. In practise this meant a choice between usage of Vicon Tracker and Vicon Nexus. Using the Tracker all segments would have been created as separate objects and in Nexus a full-body model is created. The final decision was to use Nexus and forward kinematics due to its more simple implementation.

The second problem was to find out how to merge the right-handed coordination of Nexus system with the left-handed system of Virtools so that the rotations could be transferred correctly to the DHM. It was soon found out that there was no way to do it by means of adjusting the settings of either software, so the conversion had to be done computationally.



The discovery of the solution was a long and taxing task, but finally the solution was found by simply switching second and third rows and columns in rotation matrices as shown in Figure 14. In practise this means the commutation of y-axis and z-axis.

In addition to different global axis systems, some of the corresponding body segments in Nexus and in DHM had different local axis systems. This issue was resolved by adding cells to define the set of *Local Dir* and *Local Up* axes to the segment object array in Virtools to achieve the desired orientations that correspond to the ones in Nexus. Local Dir defines the direction of local z-axis and Local Up defines the direction of local y-axis. When these are set correctly the x-axis automatically points to the right direction.

One of the most essential issues was the one concerning the tracking suit. The suit that comes with the Vicon system is not flexible enough for different body sizes and it is not very pleasant to wear. Therefore there was an attempt to create an own set of wearable equipment that would consist of separate vest, elbow and knee pads, stereo classes for head tracking in addition to the shoes and gloves of the initial suit. However the attempt to make the suit work stably enough failed and therefore the initial tracking suit had to be taken into use again. With the tracking suit the mobilization of the ready Vicon Plug-in-gait model was possible and thereby the stability of the tracking was significantly improved.

The analysis methods to implement were also contemplated. The first intention was to implement a few analysis systems, but due to time shortage only the RULA method was implemented. However the implementation is done in such a way that it is easy to copy and adapt the analysis model into additional posture analysis method models. RULA was selected as the method first implemented because it is a commonly used and universally applicable method.

In system validation the test setting caused some issues. When the work place was positioned in the middle of the capture volume, the table blocked some of the cameras in the front and therefore caused lots of occlusion problems in tracking. The post was decided to place in front of the white screen and though some occlusion problems remained, the stability got better. However this caused a new issue when the video camera was not possible to place to record straight from the side and hence the estimation of joint angles in manual evaluation was more difficult. Thereby it was decided to allow one number variation in validation data analysis results between manual and automatic evaluation.

Probably the most essential issue was the lack of stability in tracking. In Nexus there is no run time gap filling available and therefore when the model breaks during evaluation there is not much to do for its correction. The only possibility is to reselect the subject in subjects list, and that is risky since it may cause the whole model to break. Therefore the model has to be made extremely stabile so that it does not break due to subject bending or other reason for marker occlusion. There was no eligible solution found for the issue, but it is vital to find one to make the system feasible in the future.

6. RESULTS

In this chapter the thesis results are discussed. First the resulting system is introduced and after that the results of system validation are presented. Finally the potential applications of the system are considered.

6.1 Resulting system

The system is built based on two separate software, 3DVIA Virtools and Vicon Nexus. Using Vicon DataStream software development kit (SDK) and Virtools SDK a set of Virtools building blocks (BBs) that implement the tracking data streamed from Vicon to Virtools was developed. The tracking data is then used to control the DHM and based on DHM segment orientations a RULA analysis is executed. The RULA is implemented in a separate building block, also developed with Virtools SDK. The building block gives out a RULA final score which is shown on the screen during run time. The score is color-coded with red meaning bad posture, yellow an intermediate posture and green an acceptable posture. At run time there is also a button called *Play last RULA capture* displayed on the screen. The button is used for viewing last capture data, it does not redo the analysis.

The final score and additional 15 provisional scores are also printed to a text file, from which it can be exported to datasheet software such as Excel for data handling and visualization.s for the RULA BB.

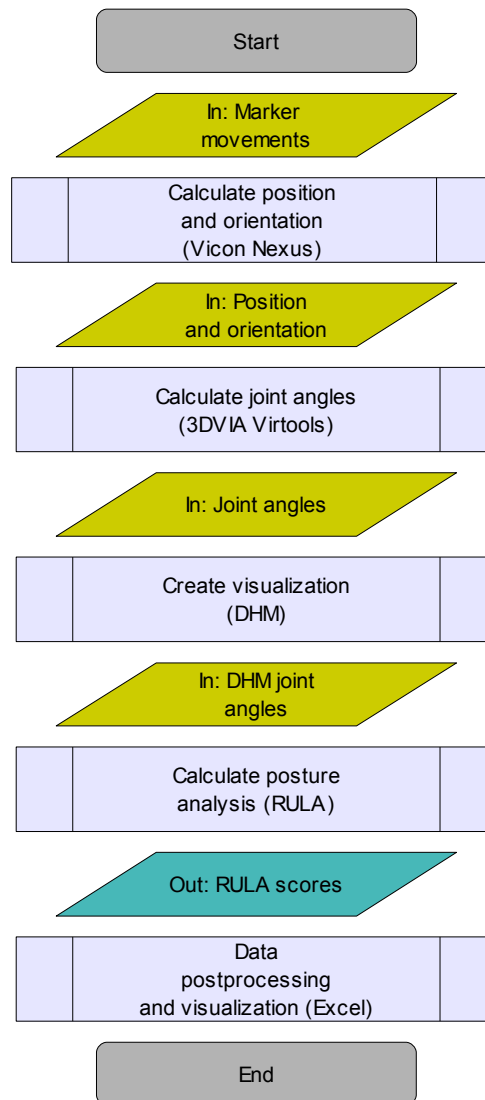


Figure 15: System flowchart.

The system flowchart is illustrated in Figure 15. The system takes movement data as an input marker that is then formed into 3D tracking data (position and orientation) in Vicon Nexus. Position and orientation data is then streamed to Virtools, where the joint angles are calculated and the visualization is done by controlling the DHM according to the joint values. The RULA analysis is then executed by DHM joint angles. RULA gives out its final score and the scores are also written into a text file. The text file is then exported to a datasheet software for data handling and visualization. The filename and path are predefined as an input of RULA-BB.

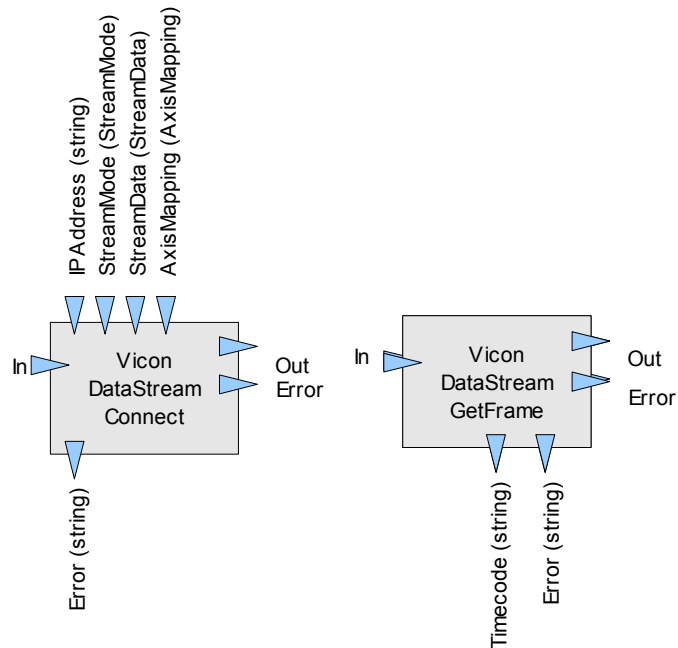


Figure 16: Connection Building Blocks.

The building blocks responsible for creating and maintaining the connection between the two software are illustrated in Figure 16. *Vicon DataStream Connect* opens the connection. It takes the IP Address of the computer running Vicon nexus as a parameter. In addition the stream mode, stream data and axis mapping can be set from predefined options. *Vicon DataStream GetFrame* fetches one frame of tracking data from Nexus.

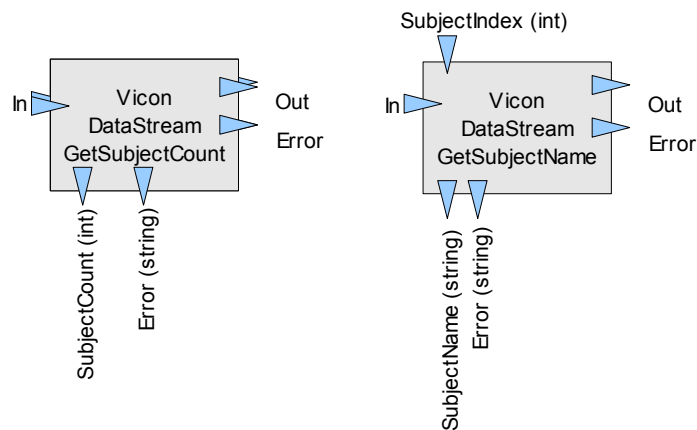


Figure 17: Subject Building Blocks.

In Figure 17 the BBs employing subject data are illustrated. *Vicon DataStream GetSubjectCount* is used for finding out how many subjects there are in use in Nexus. *ViconDataStream GetSubjectName* is used for finding out the name of the subject with certain index.

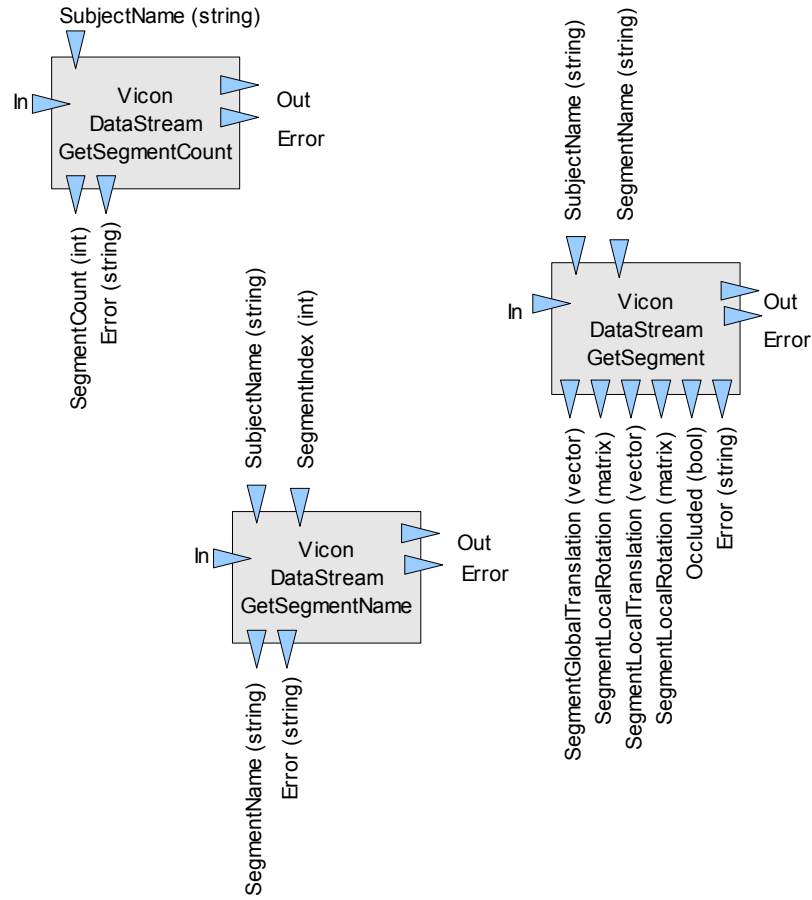


Figure 18: Segment Building Blocks.

The BBs considering subjects segments are illustrated in Figure 18. The segment building blocks are the ones used for direct DHM controlling. *Vicon DataStream GetSegmentCount* is used for finding out the number of segments, *Vicon DataStream GetSegmentName* for segment identification and *Vicon DataStream GetSegment* gives out direct information about the position and orientation of certain segments.

6.2 System validation result

In this chapter the results of system validation are presented. The chapter divides in three sections; first the group statistics are introduced, second the post testing interview data are discussed, and finally the results of manual and automated analysis comparison are covered.

6.2.1 Test user group statistics

For collecting test user statistics to describe the group, some personal information was collected with survey form (Appendix 1). The group consisted of seven 26-37 years old people. Three (43%) of the test users were women and four (57%) were men. Two of the users were university students of technology. Four of them were Masters of Science and one of them a Bachelor of Culture and Arts.

Four of the test users had never plied manual assembly jobs. Three of them had had assembly summer jobs in different industrial manufactures. The test users did not have any significant physical impediments that might have affected the results.

6.2.2 Final interview data

As a part of the final interview, right after testing the users were asked to fill in *NASA Task Load Index Form*, *NASA-TLX* (Appendix 2). The index is used for estimation of task load according to six different factors. The average values of user estimated task load factors on scale 1 to 20 are represented in table 5.

Table 5: NASA-TLX average values of user estimations on scale 1 to 20.

| Factor | Description | Scale | Average value |
|-----------------|--|--------------------------------|---------------|
| Mental demand | Mental demandingness. | Very low (1) ...Very high (20) | 2,83 |
| Physical demand | Physical demandingness. | Very low (1) ...Very high (20) | 4,67 |
| Temporal demand | Hurriedness in pace of the task. | Very low (1) ...Very high (20) | 7,83 |
| Performance | Success in own level of performance accomplishment. | Perfect (1) ... Failure (20) | 3,33 |
| Effort | Effort put in accomplishing own level of performance. | Very low (1) ...Very high (20) | 4,33 |
| Frustration | Sense of insecurity, discourage, irritation, stress and annoyance. | Very low (1) ...Very high (20) | 7,17 |

The table shows that few of the factors were estimated close to either edge. It is notable that all of the factor average values remained below the middle point on the scale. This shows that the task load was not high and therefore the result scores on postural analysis presumably should not have been high either.

The same trend was also seen in final interview results. The most remarkable cause of discomfort was the tracking suit. Users found the ribbon around fingers holding the

hand part on right position as most uncomfortable part. Also tightness and sweatyness of the suit came up in the interview.

6.2.3 Postural analysis results

The first two test cases had to be left out of data analysis. In the first test case the suit did not work so only the questions considering the comfortability of the suit were taken into account. In the second case the animation file was overwritten due to a naming mistake, so the location of analysing points could not be done. This leads to a conclusion that the file name should be set automatically to eliminate consequences of unintentional overwriting.

Table 6 presents a summary of automatic and manual analysis scores. The disparities shown in scores seem to follow up DHM calibration flaws. The final scores do not match manual analysis, for the calibration issues affect the result score so severely. That is why the analysis was finally done considering all the provisional results. It was discovered that even a small calibration flaw could affect the provisional scores by several numbers due to the emphases in the method algorithms. The orientation of the cap on subjects head caused lots of errors, so it is important to see that the cap is positioned upright. Also the fitting of the suit needs to be considered further, for it caused a lot of error in tracking.

One factor affecting the results was inaccuracy of the manual evaluation. This was partially caused by inexperience of the performer, but also the angle of view on the video recording, which made the estimation of angles difficult. The viewpoint was not straight from one side because the table used on testing caused too much occlusion on tracking when it was positioned in the middle of capture volume, so it had to be placed very close to the white screen and video recording from side was not possible. The close location to the screen caused also occlusion on markers on subjects front, which contributed the instability of the tracking data.

Table 6: Comparison between manual and automatic analysis data and segments causing disparities in cases.

| | | 1 (1...7) | 2 (1...7) | 3 (1...7) | 4 (1...7) | 5 (1...7) | 6 (1...7) | 7 (1...7) | 8 (1...7) | OTHER |
|---|----------|---------------------|---------------------|---------------------|---------------------|---|---------------------|---------------------|---------------------|---|
| CASE 1 | a | - | - | - | - | - | - | - | - | Test failed due to tracking problems. No data to analyze. |
| | m | - | - | - | - | - | - | - | - | |
| | | - | - | - | - | - | - | - | - | |
| CASE 2 | a | - | - | - | - | - | - | - | - | Analyzation failure. |
| | m | - | - | - | - | - | - | - | - | |
| | | - | - | - | - | - | - | - | - | |
| CASE 3 | a | 6 | 3 | 5 | 7 | 6 | 5 | 4 | 7 | Analysis data run out before last comparison. |
| | m | 4 | 5 | 5 | 6 | 4 | 5 | 3 | - | |
| | | w | n, u, l, w | u, w | n, w | n, b, u, w | b, w | u, wt | - | |
| CASE 4 | a | 3 | 4 | 7 | 3 | 3 | 5 | 3 | 6 | Suit remarkably loose fitted. |
| | m | 6 | 5 | 5 | 6 | 6 | 5 | 5 | 5 | |
| | | n, b, w | n, b, w | n, w | n, b, w | b, u, w | u, w | u, w | u, w | |
| CASE 5 | a | 4 | 5 | 6 | 6 | 3 | 5 | 6 | 6 | |
| | m | 5 | 6 | 5 | 6 | 6 | 5 | 6 | 6 | |
| | | n, w | b, u, w | n, w | u | b, u | n, u, w | u | b, u, w | |
| CASE 6 | a | 5 | 5 | 7 | 6 | 4 | 7 | 5 | 5 | |
| | m | 3 | 5 | 6 | 5 | 6 | 4 | 6 | 3 | |
| | | u, l, w | n, b, w | n, u, l, w | w | b, u, w | n, u, l, w | u, w | w | |
| CASE 7 | a | 5 | 4 | 7 | 5 | 6 | - | 3 | 6 | Hat positioned a little bit too much on the back of the head. |
| | m | 6 | 4 | 6 | 4 | 3 | - | 6 | 6 | |
| | | n, w | w | n, u, w | w | w | - | n, u | b, w | |
| 1 = Reaching for an empty crate from lower shelf. 2 = Reaching for crate stuffing from left hand side. 3 = Picking up a part from right hand box. 4 = Picking up the cap from the front. 5 = Screwing the cap on. 6 = Picking up a part from front left. 7 = Closing the crate. 8 = Lifting full crate to top shelf. | | | | | | n = neck b = body u = upper arm l = lower arm w = wrist wt = wrist twist | | | | |

Table 7: Distribution of segments causing deviation in total 38 samples.

| Segment | Abbreviation | Occurrence (of 38 total) | % |
|-------------|--------------|--------------------------|----|
| Neck | n | 16 | 42 |
| Body | b | 12 | 32 |
| Upper arm | u | 21 | 55 |
| Lower arm | l | 4 | 11 |
| Wrist | w | 33 | 87 |
| Wrist twist | wt | 1 | 3 |

Table 7 presents the distributions of separate segments causing deviation between the provisional results from the manual and automated analyses. Neck appears in almost half of the total 38 samples. It can be explained by the posture of the cap for it is intuitively positioned too far on the back of the head and that is why the postures of the heads do not line up.

Body causes distribution in all of the test cases but especially in the ones (e.g. case 4) where the jacket was particularly loose fitted and therefore the markers were able to move too freely in proportion to each other.

Upper arm appears in all of the cases several times. This can be most likely accounted for the left upper arm of the DHM being positioned wrong almost all the time. The arm extension angles were also difficult to measure from the video for the angle of view was from the side and this might have caused some of the problem.

Lower arm appears almost exclusively in case 6, so it seems to be that the jacket on that specific case was not put on correctly. On the video you can see that one elbow marker is a little bit displaced. Wrist occurs as an explanatory variable in almost all of the samples. This might be due to the left hand marker and a lower arm marker being placed too symmetrically considering the wrist markers and therefore the left hand of the DHM was almost all the time turned to a wrong direction. Deviation in wrist twist scores on the other hand only occurs in one occasional sample. This shows that the wrist rotation works correctly. Lower body did not cause distribution in the comparison. This is most likely due to the stabile posture of the lower body and the position of the markers being stabile.

6.3 Application of the system

The system can be utilized in future projects as soon as the tracking and thereby setting the DHM orientation is gotten to work correctly. It will be used for real-time RULA analysis and following the same implementation principles other posture analysis methods can be implemented.

In a UCD process real-time ergonomics evaluation is a fast and efficient tool for finding problematic issues in a work process. Due to color-coding even uninitiated users can locate bad postures from workflow. In the resulting system making changes to virtual models will be easy, so the iteration round of design and testing will accelerate significantly. This means that more rounds can be executed with the same resources and therefore the ergonomic factors on the final workflow can be improved.

7. DISCUSSION

The aim of the study was to create a system consisting of motion capture and virtual reality elements and to realize certain ergonomics evaluation methods in VR exploiting motion capture data and a digital human model. The goal was not entirely achieved as the motion capture part could not be made stabile and instead of several postural analysis methods only one was put into practise. However the other goals were attained, as the motion capture data is successfully used for controlling the DHM and a RULA analysis is executed on basis of the joint values of the DHM and other posture analysis methods can be easily implemented using the same means.

System validity is hard to estimate due to motion capture problems still remaining in some parts of the system. Yet according to the user testing data the other parts of the system seem to be working properly.

The goal was to create a modular and generic system. Modularity is taken into account as the system is based on object oriented programming. The program modules are reusable and can be easily modified, as far as the interface remains the same, without having an effect to the other modules. On the other hand with more time, the system could have been created more generically by using for example some kind of intervening modules converting generic operations to the specific hardware and software. At this time the system realization is quite software specific, yet it is generic enough to be used in any kinds of future projects and not only in existing environments.

In RULA implementation some features of the method needed to be left out. For example the detection of arms being crossed or weight distribution was not able to be executed automatically. This leads into some inaccuracy compared with manual analysis. On the other hand this is compensated with joint angle measurement being significantly more accurate. However the final accuracy of the system is hard to estimate because of the motion capture trouble. Yet perhaps with a more experienced RULA evaluator and different test setting, the results might have corresponded to a higher level, because the joint angle measurements were probably not accurate enough in the manual analysis.

One of the main issues is that the Nexus software is not primarily made for real-time evaluation. Therefore it does not contain methods for real-time gap-filling, so the tracking model is extremely essential to be made stabile. However with the number of markers used in whole-body tracking the task is extremely difficult to fulfill.

Use of wearable equipment did on some level make the evaluation more complex. The suit was not comfortable to wear and in most cases it did not fit well enough and

therefore caused inaccuracy to evaluation data. The creation of optimal tracking suit that would cover whole body fittedly without being uncomfortable or discomfited, is the most vital subject to be considered to make the system fit for use in real-life projects.

8. CONCLUSION

The aim of this thesis was to create a system for manual work evaluation in virtual environment utilizing digital human model. Due to stability problems still remaining in tracking section, the task could not be entirely completed, but in other parts the goals were achieved.

The system creates a link between tracking software Vicon Nexus and virtual reality operating software 3DVIA Virtools. The tracking data is streamed from Nexus to Virtools and the data is converted from the right-handed coordination system of Vicon to the left-handed system of Virtools. According to the resulting tracking data a digital human model is controlled and on the grounds of its joint values a RULA posture analysis is carried out. The RULA module was created based on a pre-existing code block.

In addition the system validity was examined through user testing. Manual RULA analysis was done for each test case and the results were compared to RULA results automatically generated by the system. In test data analysis, it was found that apart from issues concerning the DHM stability, the system seems to be working correctly. The DHM functioning and exactitude is the most essential target for further development to make evaluation results accurate.

As soon as the tracking part is gotten to work properly, the system should be fit for use in future projects. The thesis results can be ultimately considered only after the tracking part is gotten to work correctly. However the resulting system should be of use in future projects, particularly as it is implemented to a resulting system of *ManuVAR* project.

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APPENDIX 1: PERSONAL INFORMATION FORM

Name: _____

Age: _____

Occupation: _____

Education: _____

Have you ever worked on some kind of assembly tasks?

☐ Yes

☐ No

What kind?

Have you got some physical limitations (e.g. back, shoulder or vision) that can complicate task performance?

APPENDIX 2: RESEARCH AND FILMING ASSENT FORM

The user testing of automated ergonomics analysis is a part of Riikka Käsänen's master of science thesis. The aim in testing is to compare the results of manual and automated analysis. The test consists of a manual assembly task and automated RULA analysis of its ergonomical factors through motion capture. The test is filmed and the same assembly task is then manually evaluated according to the recording. Finally the results are compared to each other and the results are reported in the thesis.

Test user's personal information is gathered with a personal information form, so that the testing group can be generally described in the thesis. Individual test user's personal data is not published nor used in any other than named purpose or conveyed further.

I _____ am taking part in the testing as a test user and I give my assent for the test case to be video recorded. The recording will only be used in manual evaluation of ergonomics aspects and it will not be shown or conveyed for third parties.

Signature and date

In Tampere _____

Riikka Käsänen

APPENDIX 3: NASA TASK LOAD INDEX FORM

Figure 8.6

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

| | | |
|------|------|------|
| | | |
| Name | Task | Date |

Mental Demand How mentally demanding was the task?

Very Low
Very High

Physical Demand How physically demanding was the task?

Very Low
Very High

Temporal Demand How hurried or rushed was the pace of the task?

Very Low
Very High

Performance How successful were you in accomplishing what you were asked to do?

Perfect
Failure

Effort How hard did you have to work to accomplish your level of performance?

Very Low
Very High

Frustration How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low
Very High