ABSTRACT

Home- and workplace-adaptations for people with disabilities is an area with great variation in resource requirements and complexity, depending on the end-user's abilities and needs, and it is of vital importance that the design is optimized considering the human-environment interactions. All involved persons in such a planning process must be given sufficient support in understanding the information, so that they can participate actively. Otherwise, there is an apparent risk that discussions will be kept between experts, due to difficulties in understanding the complex and technical adaptation issues.

This thesis investigates the use of computer-based tools for planning/designing environments for physically disabled people. A software prototype, and a method to use such a tool in the planning process, was developed and evaluated, based on the findings from six case studies of real planning situations. The case studies indicated that although such a tool would support the design, as well as the dialog between the participants, a certain level of technical and economic efficiency must be obtained. The extra time spent on designing and evaluating the 3D models must be found worthwhile to the professional planner, for instance in terms of better designs or an improved dialog between the participants. To facilitate the professional planner's work, the most important issue is to maintain a large library of 3D objects.

With the latest Macintosh- and PC-based prototype versions, it was found that such a planning tool can be produced, even when using consumer-oriented computer equipment. One previous critical factor, interactive manipulation of 3D objects, can now be achieved if utilizing modern graphic cards with 3D acceleration. A usability test was performed to evaluate the prototype's basic operations, involving two groups of representative future users: five occupational therapist students, and four persons with major physical impairments. Although it was found that the usability was satisfactory for the basic tasks, the test revealed several items to be improved or added in future versions.

It would be important with an integrated support for manikins, since the design of these environments involves numerous critical man-environment considerations, e.g., wheelchair accessibility, reach ability, positioning of handrails, etc. In order to aid the design and modifications of manikins, this thesis reviews and compiles published anthropometrical and biomechanical data into a uniform segment-by-segment structure. The compilation was implemented as a spreadsheet template document.

Unfortunately, all the data required to complete such a manikin database do not exist in the literature. In many cases either one must rely on extrapolations/approximations, or one has to conduct new anthropometrical or anatomical research. The development of computer-based tomography techniques, such as, magnetic resonance imaging (MRI),

has made it possible to perform measurements on living subjects. Thus making it possible to supplement/refine available biomechanical data without many of the problems associated with cadaver studies. An MRI investigation of the neck-shoulder region was performed on 20 healthy Scandinavian, female volunteers, measuring various musculoskeletal properties. These measurements could be used for further refinements of manikin specifications and biomechanical models.

LIST OF PAPERS

This thesis is based on the following papers, hereafter referred to by their Roman numerals:

I. Bengtsson P., Johansson C.R., Eriksson J., Johansson G., af Klercker J., and Akselsson K.R. (1996). "Computer-aided planning of production, working and residentual environments". *Int. J. Indus. Ergonomics*, vol. 17: 59-68.

II. Eriksson J., Johansson G., and Akselsson K.R. (1995). "A Planning Tool Prototype for Environment Adaptations". *IEEE Trans. on Rehabilitation Engineering*, vol. 3: 283-287.

III. Eriksson J., and Johansson G. (1996). "Adaptation of Workplaces and Homes for Disabled People Using Computer Aided Design". *Int. J. Indus. Ergonomics*, vol. 17 (Special Issue: Rehabilitation Engineering): 153-162.

IV. Riedel O., Eriksson J., and Rössler A. (1993). "Planning environments for disabled people in virtual worlds". In *Proceedings of First Eurographics Workshop on Virtual Reality,* (ed. M. Goebel): 17-20.

V. Eriksson J., Ek Å., and Johansson G. "Environment Adaptations for People with Physical Disabilities: Design and Evaluation of a Software Prototype for Participatory Planning". Submitted paper.

VI. Eriksson J., Bojsen-Møller F., Juul-Kristensen B., Finsen L., Bolling M., Ståhlberg F., Larsson E.M. and Johansson G. "Measurements of Kinematic Properties of the Cervical Spine Using Magnetic Resonance Imaging". Submitted paper.

VII. Eriksson J. (1998). "A Spreadsheet Template for Supporting the Design of Computer-based Manikins". Technical Report. Dept. of Industrial Engineering, Lund Institute of Technology, Lund University.

1. INTRODUCTION

TOOLS FOR PARTICIPATORY PLANNING

Today, the concept of *participatory planning* is widely accepted and practiced in many areas of ergonomics, for instance, workplace design, work organization, production organization, and product design (Imada, 1991). The basic idea is to involve people in planning and controlling a significant amount of their own future activities. The planning should be viewed as an iterative process, where as many affected people as possible should be involved in successive work-group meetings. It is important that this involvement is not merely to inform people on plans already decided, but rather to solicit their genuine and active influence throughout the process (Shipley, 1990). Wilson & Haines (1997) describe a wide range of tools and methods that have been used in different planning situations, from simple flow-charts to advanced computerized applications. The selection of an appropriate tool or method, should be determined according to the context of planning and the participants' expertise. They conclude that the "natural" participants in a planning group should have enough skills and knowledge to use the appropriate tool themselves (although having the possibility to call in assistance from experts when needed).

Computer-based tools that support the process of participatory planning may be categorized under *Computer-Supported Cooperative Work* (CSCW) or *Groupware* (Grudin, 1995). These terms usually describe systems with multiple simultaneous users, and with network distribution capabilities. One can recognize similarities in the activities supported, and in the challenges that need to be faced; both areas aim to assist activities carried out by groups of collaborating individuals. Both areas also recognize the difficulties in developing usable and accepted systems that must satisfy people with varying levels of knowledge and abilities. Baecker et al. (1995) regard CSCW as a shift of focus in computer usage from human-machine interaction to human-human interaction, i.e., the computer facilitates the communication rather than acts as a computational device.

One example of a computer-based technique that directly addresses participatory planning was developed and evaluated within the DBDB[1]-project (Akselsson et al., 1990; Bengtsson et al., 1991; Akselsson et al., 1994). These studies present a visualization and animation technique for the planning of industrial production and organization, where the product lines and the workers' actions are described by computer images and animations. It was found that such visualizations supported the understanding and communication among the participants. Workers that formerly had

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[1] Swedish abbreviation: "Dynamisk Beskrivning med Datorstödd Bild".

minor influence in the production planning, could better contribute their specific knowledge and own suggestions.

ENVIRONMENT ADAPTATIONS FOR PHYSICALLY DISABLED PEOPLE

Home- and workplace-adaptations for people with disabilities is an area with great variation in resource requirements and complexity, heavily dependent upon the end-user's abilities and needs, and it is of vital importance that the adaptation/construction is optimized considering the human-environment interactions. The adaptation design may require various expertise from different professionals, such as, occupational therapists, construction engineers, architects, etc.

The extent of rules and legislation guiding and regulating such designs varies in different countries. In the United States, for example, guidance can be found in the Americans with Disabilities Act[2] (Ellek, 1991), and the American National Standards Institute[3] (ANSI). Also, one may find examples of non-legislative recommendations in literature, such as, Goldsmith (1976), who catalogues a large number of design recommendations in this area. In Sweden, rules and guidance can be found in Boverkets byggregler (1994), and in Handikappinstitutet (1995).

It is clear, however, that neither professional experts nor written regulations can single-handedly provide all the widespread experience needed in order to obtain fully satisfactory solutions. Instead, it is important that the planning is conducted as teamwork, where the participants may contribute with their unique experiences and knowledge. In field studies by Lifchez (1987) for example, some design projects by architect students were conducted in which disabled people attended as consultants. These consultants were found to add unique knowledge and experience to the project groups, and many issues were raised that would have been otherwise overlooked, indicating that the quality of a design greatly benefits from such cooperation in the design phase.

It is often an occupational therapist (OT) that conducts an environmental and functional assessment in order to obtain a barrier-free environment. The OT together with the end-user, tries out the equipment and consults with medical expertise, funding organizations, architects, engineers, etc. In Scandinavia, and in many other European countries, it is therefore usually an OT who has the coordinating role when planning for adaptations of interior environments (note that "environment" is referring not only to constructional aspects of buildings, but also to furniture and equipment). Regarding the situation in the

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[2] Americans with Disabilities Act (1990): Public Law 101-336.

[3] American National Standards Institute (1980): Specifications for making buildings and facilities accessible to, and usable by, the physically handicapped.

United States, environment adaptations are according to the American Occupational Therapy Association, clearly within the scope of the OT profession (American Occupational Therapy Association, 1981 and 1983). Taira (1984) and Acheson-Cooper et al. (1991) argue for an increased role for OTs in environmental adaptations, but there may still be situations where architects or engineers have the coordinating role instead (depending on the nature of the adaptations, and/or traditions of different states).

The end-user has a right, as well as an obligation, to take active part in the planning process (Statens Offentliga Utredningar, 1991). Furthermore, adaptations may also affect relatives, home-service personnel and work-colleagues, to varying extents. These people should also be able to influence what is planned. Therefore, it is important with a series of planning sessions where all people involved can communicate and forward suggestions on equal terms. To aid such a planning and design process, one may use a wide variety of tools and techniques. An example of a simple and common technique is using sketches or drawings together with paper-clippings that represent furniture and equipment. By moving around these clippings, the participants can elaborate on different solutions, and test accessibility, for example. Full-scale modeling have also been extensively used for participative design of environments in these areas (Paulsson, 1974; Hornyanszky-Dalholm & Rydberg-Mitchell, 1992).

A COMPUTER-BASED TOOL FOR PLANNING AND DESIGN

In the area of planning environments for physically disabled people, one may use a similar approach as in the DBDB method: a computer-based planning tool could be used to support communication among the individuals of the planning group, and facilitate the understanding of what is being planned. There are, of course, large differences between the planning situations in the DBDB project and the typical planning situations in adaptations for physically disabled. The latter case may, for instance, demand an accurate design and evaluation of the man-environment for one or a few individuals with special needs. Hence, one may need means for direct and easy-to-use modeling and re-modeling of different design suggestions.

Although it is important to consider *everyone* involved in a planning process as users to such a tool, one person is needed to introduce the tool into the process, as well as to provide basic support. In Sweden and in many other countries, it is often OTs who have the overall responsibility for supervising and arranging adaptations for disabled people. Hence, these professionals may be regarded as the primary operators of the tool, but at the same time, the end-users as well as others involved in the process should be encouraged to make use of the tool, making their own suggestions or changes (independently or together with the OT).

In conclusion, a tool for planning environments for physically disabled people should meet the following criteria on *usefulness*:

- Aid the professional planner (for instance, an OT) in ergonomical design taking into consideration an individual's abilities and disabilities.

- Support communication, and facilitate understanding of what is planned, for the benefit of all the people involved.

- Encourage active participation from all the people involved.

To be generally accepted and used in these planning situations, such a system must also fulfill some general demands on technical and economic *efficiency*:

- It is important that the planning process does not become delayed or unnecessarily complicated as a result of using such a tool.

- It is also important that the expenses in purchasing and maintaining such a planning tool are moderate.

- As there may be considerable variation in computer experience among the persons involved in a planning process, such a planning tool must be easy to learn and easy to use, especially concerning tasks that are frequent during planning sessions, e.g. conducting walkthroughs or moving objects.

Given the second objective on technical/economic efficiency, it would be a major advantage if such a software could be hosted on an ordinary personal computer, rather than on a workstation or other high-performance (and expensive) platform.

Modeling with 3D graphics has perhaps its longest tradition in Computer Aided Design (CAD), where it has been serving as a professional tool for engineers, designers and architects, etc., for the last three decades. CAD systems have been frequently used in workplace evaluation, as well as in architectural design. In recent years, the area of interactive 3D graphics has gone through a rapid development, and now modeling with 3D graphics can be found in a wide variety of applications, and is today often used by illustrators, animators, game developers, etc. Any application for computer-based design and visualization obviously shares many features with traditional CAD systems, but regarding the area of participatory planning, such a tool may be regarded as the *means for communication*, rather than the production of complete and formal design specifications (plotted out as correct drawings, for instance). Thus, the degree of accuracy of the design can be treated more flexibly, whereas the important objective lies in supporting communication and promoting better understanding during the planning process.

When using a 3D graphics accelerator card, it is now possible for a PC or Macintosh to perform real-time rendering of 3D models, with a quality that was proprietary to UNIX-based workstations or high-end computers up until only a few years ago. Although personal computers generally perform less than average workstations, there would be several benefits in utilizing personal computers as a platform:

- Both hardware and software are considerably cheaper.
- Users may often already own and be familiar with such a system.
- The computer can also be used for running common programs (word-processing, internet browsing, etc.).

If a model of a human body, also called a manikin or mannequin, is incorporated into the design, it is possible to assess postural comfort, clearance, reach, vision, etc. By adding biomechanical calculations to the system, it is also possible to simulate workload. When designing environments for physically disabled people, there can be numerous critical aspects to consider, such as, wheelchair accessibility, reach abilities, positioning of handles and handrails, etc. Therefore, a planning tool for physically disabled people should support the evaluation and elaboration using manikins.

Manikins for ergonomic evaluation have existed, as built-in features or external options for various CAD systems, ever since the 1960's, where SAMMIE was a European pioneer system (Porter & Case, 1980). By placing models of humans into the CAD model, it was possible to evaluate ergonomic aspects much earlier in a design process (Dooley, 1982; Porter et al., 1990). There are today many sophisticated and powerful software packages for advanced ergonomic analysis and design, for instance, JACK (Badler, 1991), SafeWork (Genicom Consultants Inc.), Anthropos (Delta Industries GmbH, Ramsis (TecMath GmbH), etc.

Although these packages feature many useful techniques and solutions, it would for several reasons be difficult to immediately use these as a more or less integrated part of a low cost, simple software application:

- In some cases, these packages may require a certain CAD-system, which can be very expensive.
- They are often supported exclusively by UNIX-based workstations.
- Much of the data and algorithms are unpublished or even confidential, and thus it is difficult to compare results with other packages.
- The interfaces are at large influenced by CAD systems, in that they are complex and expert-oriented.

Another concern about incorporating manikins is the question of their validity in size and behavior. In other words, are they anthropometrically correct, and is the mechanical behavior a good model of humans? There are many difficulties in assessing the validity of different manikins, and making comparisons between different systems. One reason is that much data for several critical characteristics simply do not exist in the literature, and therefore, extrapolations or estimates have to be made by the designers of the manikin systems. Another reason is that program developers do not sufficiently report their sources of anthropometric data, and/or how their own estimations were performed. There may, of course, be commercial reasons behind not revealing proprietary databases to competitors.

Two of the most influential data sources for biomechanical modeling are the work of Dempster (1955), and NASA's Anthropometric Source Book (1978). Although the data sets in these publications are widely accepted and used, there are certain body parts that are described with less detail and uniformity, such as, various parts of the trunk. Furthermore, it should be observed that much of this data has been based on cadaver studies, where a limited selection of specimens has been available (Dempster's study, for example, included 8 cadavers, all of which were males, and the known age ranged from 52 to 83 years). A well-known concern about cadaver studies is the presumed anomalies compared to living tissue, for example, the increase in circumference due to the use of embalming fluids for compensating dehydration, as well as other postmortem effects (Clauser et al., 1969). Hence, there are several advantages in performing anatomical measurements on living subjects. The development of computer-based tomography techniques, such as, Computed X-ray Tomography (CT) and Magnetic Resonance Imaging (MRI), have made it possible to perform *in vivo* anatomical measurements. Thus providing the possibility of supplementing available biomechanical data without many of the problems associated with cadaver studies.

THE SCOPE OF THIS THESIS

This thesis investigates the possibilities of using a computer-based tool for planning and designing environments for physically disabled people. A software prototype and a method to use such a tool in the planning process, was initially based on the DBDB-technique (Paper I), and later further developed and evaluated through findings from six case studies of real planning situations regarding environment adaptations (Papers II, III, IV, V). Since such a planning tool should support the use of manikins, the design and integration of this feature are of particular interest. Paper VII in this thesis reviews and compiles published anthropometric and biomechanic data into a uniform three-dimensional nomenclature. The compilation of data resulted in a manikin "template" document, to be used with a spreadsheet program. Paper VI presents some anatomical measurements of the neck-shoulder region from a study using a Magnetic Resonance Imaging (MRI) scanner. These measurements are intended as data for improved biomechanical modeling and more detailed designs of manikins.

2. COMPUTER GRAPHICS FOR PARTICIPATORY PLANNING AND DESIGN

SUMMARY OF PAPER I

Introduction

Traditionally in industrial planning, the design process of production systems initially focuses on technical and economical factors. Work organization and human factors are often handled at later stages in the planning process, and in some cases more or less neglected (Corbett, 1990). Mistakes involving the work environment are often difficult and costly to adjust at later stages. Hence, ergonomists and human factors specialists, in cooperation with managers and worker representatives, can make significant contributions if they are involved from the beginning of a design project.

Computer visualization may be a tool for presentation of design ideas and for facilitation of the dialogue in planning groups whose members have different backgrounds in experience and education. The DBDB method was used to investigate this idea (Akselsson et al., 1990; Bengtsson et al., 1991). DBDB stands for "Dynamisk Beskrivning med Datorstödd Bild", which correspond in English to: Dynamic Description with Computer supported Pictures.

This paper discusses the DBDB method and its applicability for the planning of new environments. Emphasis is placed on the possibility of visualizing design ideas and facilitating dialogue in planning groups with members who have different backgrounds in experience and education, by means of the computer-aided planning technique. The fundamental reasoning was that there are situations where visual presentations are easier to understand than verbal or written presentations.

Theories and methods

The DBDB methodology consists of:

- A technique for computer modeling and visualization of environments and design proposals.
- The involvement of concerned subjects in the planning process for active participation in work-groups.

The technique was based on Macintosh computers and some commercial 3D modeling packages, such as, *Swivel 3D Professional* and *Modelshop*, and the multimedia authoring program *MacroMind Director* (MacroMedia Inc.). Basically, this technique was used to produce compound images and animated sequences[4]. Together with text and sound, this could then be mixed into interactive presentations on the computer, or to be transformed into videotape or paper print-outs.

The work-group approach implies that the knowledge and experience of different professionals and other subjects concerned are utilized for optimizing the planning process and initiating change. Corporate planning groups are formed according to Likert’s linking pin concept (1967), implying that there are functioning connections in the groups between, as well as within, different organizational levels. The action research methodology applied for initiating change activities is in line with Argyris' (1985) reasoning on double-loop learning aiming at public testing of future plans. Kolb's theory of experiential learning (Wolfe & Kolb, 1991) has served as a reference for studying learning and development of professional competence in industrial settings.

Industrial case study

The case study described in this paper was carried out at a company that manufactured components for the automobile industry. In order to enhance its competitiveness, the company planned to change some parts of the production system. This necessitated recurrent discussions on how to combine technical and human factors, not only in the manufacturing process, but also in the planning process.

The industrial case study indicate that:

- an analysis of the production system is preferably done in a two-step sequence. In the first phase, concrete aspects are mapped by means of traditional techniques; while in the second phase, additional information is collected by means of computerized visualization. Mistakes and costs due to the fact that operator tasks, as well as ergonomic, social and psychological factors, are handled at a late stage in the planning process, might be reduced.
- computer supported animation can visualize complex relations between different work environment conditions, and illustrate dynamic processes that are hard to describe in drawings or in text.

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[4] In an animated sequence, each frame consists of a background picture beneath a number of partly transparent images stacked on top of each other. The images of backgrounds, such as, building blocks, were modeled and rendered in Modelshop; whereas moving objects, such as, machines and humans, were modeled, manipulated and rendered in Swivel 3D Professional. These images were then mixed and animated into sequences in MacroMind Director. A more detailed description of the animation technique can be found in Eriksson (1991).

- realistic imaging of production layouts and workplaces can serve as a common pictorial language that both facilitates communication and mutual understanding among different professionals, thus overcoming communication barriers (as suggested by Hall, 1991).
- abstract factors associated with economic, social and psychological conditions in the work environment are more difficult to animate and describe in pictures.

PLANNING ENVIRONMENTS FOR PHYSICALLY DISABLED PEOPLE

In a project called DABAR[5], conducted at the Division of Ergonomics and Aerosol Technology, Lund Institute of Technology, the possibilities with a computer-based tool for planning environments for physically disabled people were investigated. The general objectives were as follows:

1. Defining the needs and requirements in real planning situations, in terms of how the OTs work, what people are involved, which adaptation alternatives are discussed and how these evolve.
2. Developing and evaluating a prototype of the planning tool in real planning situations.
3. Defining when and how to integrate the planning tool in the planning process.

Since we considered *everyone* involved in a planning process as potential users of such a tool, it was found necessary to study real planning situations, where different kinds of users participated (Eriksson & Johansson, 1993). Hence, a case-study approach was employed, involving 6 cases of environment planning for physically disabled people.

Paper II deals with objective #2: the development and evaluation of a prototype, and paper III deals with objectives #1 and #3: what is needed and required in a planning tool (i.e. how the OTs work, what people are involved, which adaptation alternatives are discussed, how these evolve, etc.), and the integration of a tool in the planning process (e.g. under what circumstances a tool can be of best use).

Case study methodology

Similarly to the DBDB method, the case studies were performed with an action research approach, where the researcher to some extent needed to take part in the cases. Besides

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[5] Swedish abbreviation: "Datorstödd Anpassning av Bostäder och Arbetsplatser för Rörelsehindrade", which correspond in English to: computer aided home and workplace adaptations for physically disabled people.

making observations, the researcher was mainly active in operating the computer and preparing 3D models. The researcher was not, however, allowed to influence what was planned. Since the case studies were performed at different stages of the prototype development, the research method had to be adapted to these stages in terms of how much the planning tool could be utilized, and hence, what was to be evaluated and observed. The activity and intervention in each case, as well as relevant issues of research were defined in four phases:

Phase I aimed mainly at learning about the present rehabilitation situation, e.g. how planning was carried out, which people were involved, to what extent they participated actively, what conflicts could arise, etc. The researcher made observations during the planning process. The animated sequences, produced by the tool, were not presented to the participants until after the adaptations had been decided upon. Hence, the interference with the normal planning process was expected to be minor. Case studies 1 and 2 were performed in this phase. Both cases mainly concerned workplace accessibility.

In phase II, the planning tool was introduced as an alternative method when different solutions had already been drafted. Case study 3, dealing with an office adaptation, was performed in this phase. After the completed process, the participants were given a questionnaire about the tool's usefulness, performance and necessary improvements. Additional questions were addressed to the OT: the method of work, average number of planning meetings and people attending, pros and cons of the present situation, etc.

In phase III, the tool was used as the primary design tool throughout the planning process. Case 4 dealt with a receptionist's work-place, while cases 5 and 6 concerned domestic adaptations. Observations were documented as in phase II, and the participants' opinions were also surveyed by questionnaires and interviews.

Regarding phase IV, for which there has not yet been any study performed, no external researcher were to intervene in the planning sessions. Instead, the OT would document the observations and handle the computer. The researchers involvement would be restricted to consultative support, such as, 3D modeling, and to evaluating the case with questionnaires and interviews before and after the planning process.

SUMMARY OF PAPER II

Prototype development

The prototype development and evaluation was performed with the following objectives on *usefulness* and *efficiency*:

The tool should be *useful* for:
- aiding design with respect to an individual's abilities and disabilities;
- supporting communication among all participants and facilitating their understanding of what is planned;
- encouraging an active participation from all the people involved.

The tool should be technically and economically *efficient* regarding:
- obtaining an acceptable ratio between the quality of the result and the effort/time spent on the planning;
- simplicity in learning and using;
- moderate expenses in purchasing and maintaining a system.

The initial prototype was based on a similar modeling and animation technique as in the DBDB-study (see Paper I). However, it was found that although animations were valuable in visualizing and explaining complex adaptations, the technique required much time, as well as good skills in matching projections of 3D models from different programs with respect to size, view-angle, degree of perspective, etc. Furthermore, in this area of environment design, it was important to evaluate an individual's interaction with the environment, such as, reach and clearance. Therefore, it must be possible to manipulate the 3D models directly. To achieve that interaction, as well as flexibility for modifications throughout the planning process, it was desirable to gather all the objects in a single 3D model. Thereby, the designs could more directly be rearranged in various combinations.

Previously made 3D objects were organized into an *object library*, from which one later could select and import objects into new environments. For best simplicity and effectiveness, it was important to develop a consistency in file format, scaling, orientation, naming/categorization, etc.

By placing a human model in the environment, an individual’s ability to interact with environment and equipment could be tested by manipulating the model into different positions and postures (e.g. concerning reach, clearance and accessibility). Human models were designed with 19 moveable segments, based on anthropometric data for a male and female North European population (Eriksson, 1994).

In order to evaluate postural load and comfort, a biomechanical program, *BioMek*, was developed (Eriksson, 1994). A manikin could be manipulated into an arbitrary posture in Swivel, and the BioMek program was then able read out the posture from the Swivel file and calculate the forces and torques in a static equilibrium for each joint in the upper body. The principles of the static force propagation algorithm that was used, can be found in Chaffin & Andersson (1984), for instance.

Evaluation of the prototype

The prototype was found to fulfill most of the objectives regarding *usefulness*:

(I) The prototype facilitated modeling and manipulating of a design. The individual's abilities and disabilities could be taken into consideration by adapting the human model's size and range of motion, and/or by placing the model in a wheelchair. The functionality could be evaluated in terms of reach, accessibility, clearance, field of view, etc. Direct manipulations of the 3D models provided flexibility for executing modifications during meetings, for instance, rearranging furniture, changing viewpoints, adjusting postures, etc.

(II) The visualizations of suggested adaptations supported the understanding, and in general, the level of details and realism was found sufficient. The 3D models could be visualized and inspected from an arbitrary view-point, but an orthographic top-view was mostly preferred when rearranging the designs. Animated sequences were primarily used for demonstrations, such as, walkthrough sequences, or when illustrating wheelchair accessibility and space requirements.

(III) The studies indicated that discussions and active participation could be improved if the visualizations supported the understanding. Furthermore, the studies indicated that the design process was enhanced by the *iterative* way of improving proposed designs. Several alternatives could be modeled at the initial stage of the process, and the people concerned were gathered to compare and discuss improvements. The prototype facilitated making modifications, or alternative versions, of the initial proposals.

Concerning *efficiency*, the prototype still had some deficiencies:

(I) The prototype may only be efficient when most of the models can be picked from an *object library*, thereby sparing ordinary users the main effort.

(II) The software and hardware expenses were expected to be acceptable (as long as personal computers are to be used), where one can anticipate a continuous increase in the performance/price ratio. Instead, the greatest expenditure of resources would probably be spent on training, technical support, and keeping an object library updated.

(III) The Swivel program was, in general, found simple to learn and to use. However, the numerical control in creating and measuring objects were not optimal. Other programs could provide better accuracy, but they were more complicated to use, and were less oriented to direct manipulation. It was also preferable to work with a single program.

SUMMARY OF PAPER III

This paper presents the observations and findings of the case studies concerning:

- what is needed and required in a typical planning situation (i.e. how the OTs work, what people are involved, which adaptation alternatives are discussed, how these evolve, etc.);
- the integration of a tool in the planning process (i.e. under what circumstances, and how, a tool can be useful and efficient).

Case studies

In case 1, the subject was a young man with muscular dystrophy, driving a manual wheelchair. The access to his new workplace was obstructed by a heavy, manual front door and two steps. The adaptations found necessary were an electric front door opener, and a platform lift with the hydraulic mechanism hidden below the floor level.

In case 2, a student with a severe case of muscular dystrophy was to gain occupational experience in an office. A major problem was accessing the office on the third floor. Several doors had to be opened manually and there were two steps between the front door and the elevators. The OT suggested a simple adaptation: a ramp over the steps which was manually folded up against the wall, when not in use.

Case study 3 involved a man with quadriplegia from a spinal injury. An OT was consulted to recommend furniture and equipment for a home-office workplace. At the initial stage of the planning process, the OT elaborated on different solutions with paper clippings, and sketched some alternative furniture combinations (see Figure 1).

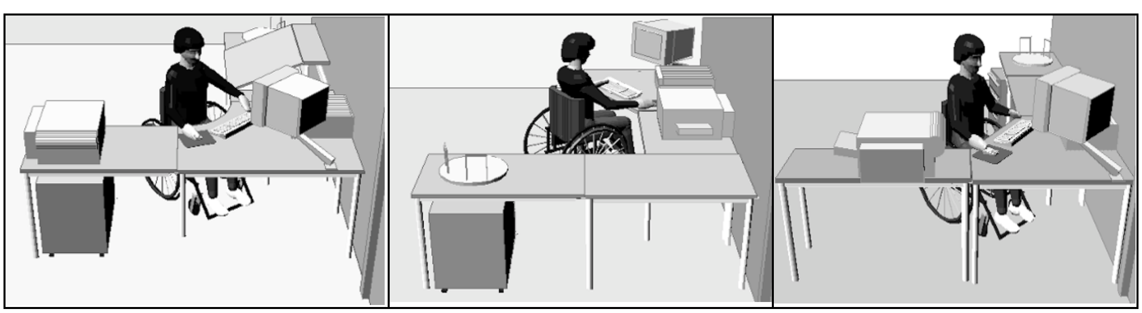

Figure 1. Three different furniture combinations, as suggested by the OT in case study 3.

In case study 4, the subject was a young nurse, whose new employment was as a receptionist at a medical center. The reception desk needed to be adapted for her short stature, and limited strength and reach, but it should also fit colleagues and patients. Three alternatives were designed and evaluated. A set of print-outs also served as a design specification for the carpenter. The final version is shown in Figure 2.

Case 5 dealt with an adaptation of a bathroom for a woman with brain and spinal injuries (paraplegia and cognition/speech impairments). The planning involved her husband, two OTs (one from the rehabilitation center and one OT responsible for the district), a district engineer responsible for municipally funded adaptations, and a home-service person.

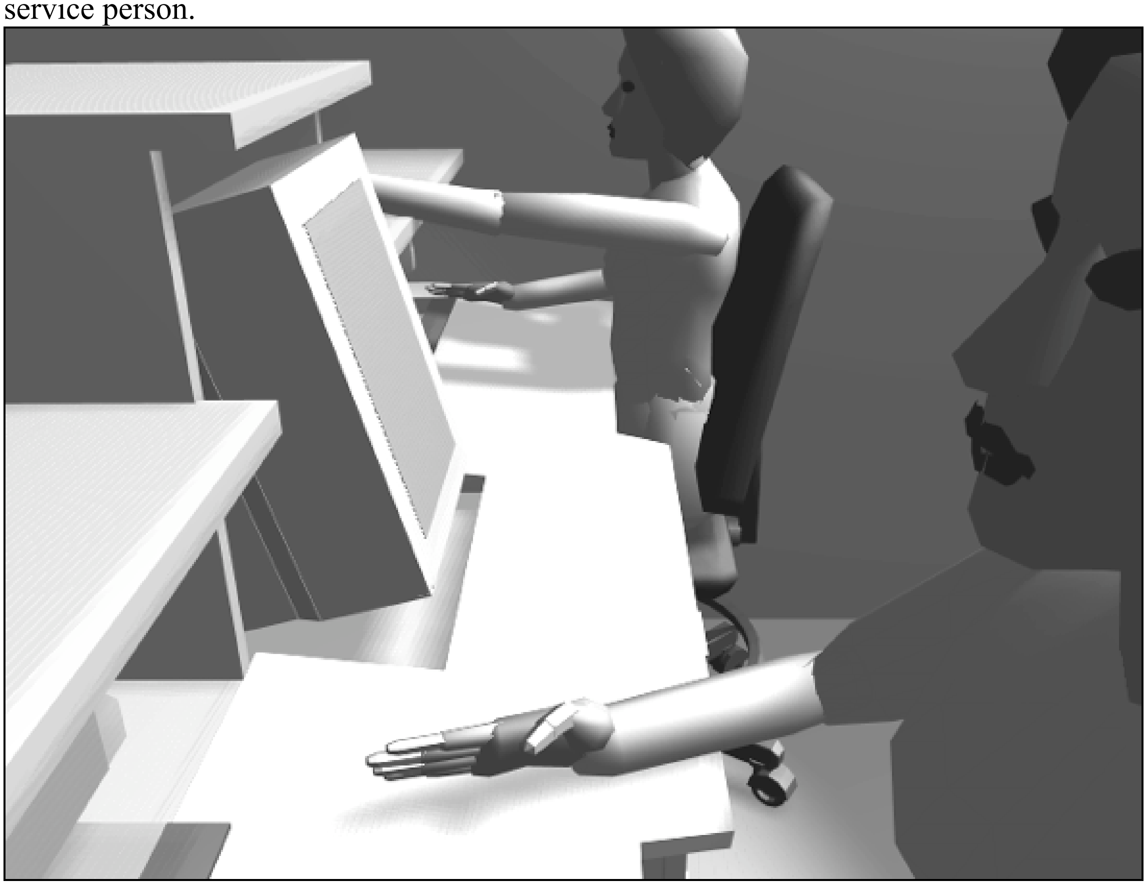

Figure 2. The final design of the reception desk of Case Study Four.

Case 6 also concerned a domestic adaptation. The subjects were a young couple, where a a spinal injury had made the woman wheelchair bound. Responsible for the adaptation were as in the previous case, one OT from a rehabilitation center, one district OT, and a district engineer. The OTs considered it necessary to adjust the kitchen floor level and re-furnish the bathroom.

Today's planning situation

In Sweden, the planning of environment adaptations for disabled people, is normally supervised by an OT. Initially, the OTs analyze the present situation, considering both the disabled person's needs and abilities, and possibilities/limitations of the environment. The data collection is based on medical files and on interviews with the disabled person (if necessary, body dimensions and constraints are measured). When evaluating space requirements, common methods are to draw sketches and place paper clippings in different arrangements, or to make a full-scale test by marking out walls and furniture on the floor with tape.

The planning is regarded as a process, based on a number of planning meetings with people concerned. The number of meetings and the people attending vary from case to case, depending partly on the individual OT's method of working. In workplace adaptations, the participants are normally the disabled person, the employer, and more rarely, colleagues, assistants and sales representatives for special equipment. For domestic adaptations, it seems as if engineers/architects and the future inhabitants do not meet face-to-face often enough. Furthermore, it seems as if some categories who also will be affected by an adaptation, for instance, home-service personnel, rarely attend planning meetings.

A potential area of conflict is funding, which naturally can have implications for the technical discussions (for instance, in what is considered necessary in construction, re-furnishing, and special equipment). For workplaces, the cost is divided between the employer and the county administration, depending on the extent of the adaptation, and whether it also addresses the rest of the personnel. For homes, necessary adaptations are funded and carried out by the municipality, represented by a district engineer.

Another conflict may occur, especially when adapting homes, about aesthetics versus functionality. For instance, good working conditions for home-service or nursing personnel may require large workspaces and special equipment such as, lifts, while the future inhabitants may oppose solutions that look too much like a hospital.

In home adaptations, the OTs and the construction engineers have different responsibilities, as well as different knowledge and experience. The OTs have the insight about the disabled person's needs and requirements, while the engineer has the knowledge about constructional aspects, and what it is technically possible to solve. If the communication between them is sparse, there is an apparent risk that the final adaptation may have many deficiencies.

Integrating a planning tool in the process

The case studies indicate that a planning tool, such as, the one prototyped here, can be used to support understanding and active participation among various kinds of participants. It also makes it possible for a professional planner to make designs of future environments and evaluate the functionality with high accuracy. Dealing with various kinds of physical impairments, it is important that the manikins can be adapted to an individual's size and physical abilities.

To take advantage of an iterative planning process, it is important that all the people concerned can attend through the whole process to a greater extent than they are doing today. For homes, it may be important to include construction engineers and nursing/home-service personnel. For workplaces, colleagues and/or assistants should be represented.

The majority of the participants in the cases answered positively regarding the prototype's usefulness in supporting the visualization of the alternatives, and for interactive re-arrangements. The answers indicated that laymen seemed to appreciate the tool mainly as a visualization aid, while the OTs and engineers emphasized the possibilities to evaluate a solution's functionality. In general, the answers indicate that people who were professionally experienced about these kinds of adaptations, required fewer details and less realism than those with no previous experience.

A frequently mentioned advantage was that mistakes could be more easily avoided. However, some participants thought that suggestions can easily be over-elaborated, and that details that are difficult to visualize risk being forgotten. Concern was also expressed that the tool itself could become too much in focus, thus diverting attention away from the actual planning issues.

Print-outs on paper were considered to be an important supplement to working on the computer directly. The print-outs could be inspected between meetings, or serve as a source of information for those who do not attend the meetings.

ENHANCED INTERACTION AND VISUALIZATION OF 3D MODELS

Viewing and interacting with a 3D model are obviously delimited when using the standard interface equipment of a computer (i.e. the mouse, keyboard, and monitor).

The term *Virtual Reality* (VR) is used to define systems where users can view and manipulate 3D models with some immersion, or sense of presence (Kalawsky, 1993).

A basic requirement on such a system is that it can respond to a user's input, and present it in what appears to be real-time. There have emerged two categories in describing such systems:

- *Immersive VR* employs equipment that serves to replace our visual, auditory and motoric senses of the real world with artificial stimuli, thus providing an impression of acting within the 3D model. The equipment includes stereoscopic head-mounted displays, stereo headphones, datagloves, spatial tracking sensors, etc.

- *Desktop VR* uses the ordinary computer monitor and input device, such as, mouse or joy-stick, to view and interact with the 3D model. The standard peripherals may be replaced or supplemented with shutter-glasses for stereoscopic projections, and joy-sticks with two, three or six degrees-of-freedom.

The planning tool discussed in this thesis could perhaps be categorized as a Desktop VR-system, but the typical interface equipment for the near future would probably continue to be the ordinary mouse, keyboard, and monitor, since most VR-interface consumer products are still rather expensive and of poor quality.

Nevertheless, the potential in enhanced interaction/visualization of 3D models is indeed promising, and the computer-game industry may be the driving force behind the development of future low-cost devices, such as, stereoscopic displays, datagloves, and 3D trackers.

The term *walkthrough* is often used for describing incremental changes of the view-point, thus simulating walking through a virtual world. Ideally, the view-point should follow the user's movements, for instance, tracked by the sensor on the headset. There are, however, several technical limitations (e.g. all the wires connected to the user, and the limited reach of magnetic sensors) which make it necessary to combine headset tracking with glove gestures. For desktop VR, one may be restricted to input from joy-sticks or keyboard.

Paper IV describes an experiment performed with one of the first commercially available immersive VR-systems (VPL Inc.), which was situated at the Fraunhofer Institute of Industrial Engineering in Stuttgart, Germany. Walkthroughs and object manipulation were performed on models that originated from case studies 3, 4 and 5.

Besides the issue of interface-products, the requirements on computer speed can be critical, especially for Desktop VR systems, as well as other PC applications offering full interaction with 3D models. *Rendering*, i.e., the process of converting the 3D representation into a projected, rasterized image on the screen, can be a very calculation-intensive task, depending on many factors: platform configuration, system performance, rendering quality, model complexity, etc. Given the objective of interactive viewing and manipulation, rendering must be performed in as near as "real-time" as possible. Normally in video, the frame-rate is 25 or 30 Hz, which is sufficient for providing the illusion of continuous motion. How much the frame-rate can be reduced and still provide a sense of presence is therefore a major concern. According to a study on the effects of lag on perceptual adoption, delays of 60 ms reduces the adoption, at 120 ms it is clearly impaired, and beyond 200 ms the presence starts to break down (Held & Durlach, 1991). For good interaction with 3D objects, the frame-rate is therefore considered to be satisfactory between 16 to 25 Hz, and reduced between 5 to 16 Hz.

In the first half of the 1990's, these demands on rendering speed could rarely be fulfilled using personal computers. Instead, this was proprietary to workstations or mainframe computers with dedicated (and expensive) hardware for 3D graphic rendering. Early 3D modeling programs for personal computers could therefore not always offer direct manipulation for moving/rotating objects, or parts of objects. The Swivel program, however, actually managed to offer a fairly acceptable level of interaction, since only a few help-lines were to be rendered during the time an object was dragged around.

Today's personal computers have enough speed for interactive 3D graphics, even for rather complex models and when using relatively advanced rendering techniques, such as, Gouraud[6] shading and texture-mapping. Special chips, designed for accelerated 3D graphics are now present in practically all new consumer graphics cards, a development rallied by the game industry. Furthermore, the major manufacturers of system software for personal computers, such as, Microsoft and Apple, now provide support for 3D graphics, as an integrated part of the operating system. Through an API (Application Programming Interface), it is possible for independent software developers to utilize services, such as rendering, directly, thus keeping their own code minimal and focused, and saving substantial development efforts. This may perhaps also lead to better consistency and compatibility among different 3D applications.

Paper V deals with the development and evaluation of a more comprehensive prototype than the ones used in the case studies. The new prototype, called *Magrathea*[7], strives to benefit from the latest developments in 3D graphics for personal computer systems (e.g. in utilizing 3D graphics APIs and accelerator cards). Technical details on this development project can be found in Löfstrand (1996), Nilsson & Vågbäck (1996), and Olsson (1997).

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[6] An interpolation technique for smoothing faceted surfaces. See Foley et al. (1990).

[7] The name Magrathea was taken from the world construction site appearing in Douglas Adams' "Hitch-hikers Guide to the Galaxy" trilogy.

SUMMARY OF PAPER IV

This paper evaluates the possibilities in using a VR-system for planning and design of environments for physically disabled people. Models that originated from the case studies 3, 4, and 5 were employed. The experiment was performed at the VR-laboratory at Fraunhofer Institute of Industrial Engineering in Stuttgart, Germany.

The VR-equipment primarily used were as follows:

- A mainframe computer, Silicon Graphics 4D440IG2RE Skywriter, used for real-time rendering.
- A VPL EyePhone, a headset with stereoscopic LCD-oculars and earphones.
- A VPL DataGlove model 2, a lycra-glove with 10 light-conductors for registration of finger-joint flexion.
- Two Polhemus Fastrack magnetic sensors for tracking of position and orientation. One sensor was attached to the glove, and one attached to the headset.

At the Fraunhofer Institute, an immersive user-interface called VIRUSI (Virtual User Interface) was developed. With this interface, the user could see a virtual "tool-belt" around his waist. The tool-belt contained 3D icons that represented various object manipulation tools: select, move, rotate, scale, and change color. With gestures tracked by the DataGlove, the user could interact with objects where the result depended on which tool was selected.

The Swivel-produced models that were used, originated from case 3 (an office workplace for a quadriplegic man), case 4 (a reception room and customized reception desk for a nurse with morbus Leri-Weil), and case 5 (a bathroom for a wheel-chair bound woman). The models from studies 4 and 5 were directly transferred to the VR-system, thus performing walkthroughs only. Model 3 was prepared for working with the VIRUSI program, thereby performing object interaction using the virtual tool-belt.

Results and discussion

The VR system offered extended possibilities in visualization and interaction with a 3D model, as compared to an ordinary computer interface. A stereoscopic headset provided the means for immersive inspections and walkthroughs of the 3D model, and the data-glove made it possible to interact with the objects.

Disadvantages with immersive VR systems were their expensiveness and that they could not be moved from the lab-environment (especially regarding the mainframe computer). Another disadvantage, especially regarding this field of application, was that only one person at a time could be in the virtual environment. It would have been desirable if two (or even more) persons could act simultaneously in the virtual environment, by using double headsets and data-gloves. VPL could offer this feature, but such equipment was not available at the Fraunhofer Institute.

In general, one can never take for granted that 3D graphic conversions between different computer platforms and software packages are done without problems and loss of information. In this case, however, the Swivel based models could be straightforwardly transferred into the VR system, at least when only performing walkthroughs (but explicit programming was required if to interact with 3D objects using gestures with the DataGlove). The reason for this was that VPL in fact had developed the program Swivel 3D Professional as a 3D modeler for its VR system.

SUMMARY OF PAPER V

Introduction

In the previously performed case studies (described in Paper III), the prototype was based on a compilation of commercially available 3D modeling programs, which revealed several limitations, regarding interactivity and supported features. Therefore, a new software prototype, named *Magrathea*, was designed and implemented, striving to benefit from the latest consumer oriented 3D graphics technology. Since the people involved in the planning process of environmental adaptations may have limited computer experience, it places great demands upon the design of the prototype's user interface, and therefore a controlled usability test was conducted on two groups of future users: occupational therapists (OTs), and disabled persons (DPs).

Review of desired features

Three OTs who had previously participated in the case studies, were interviewed regarding their experiences on using the former prototype. A list of basic operations was reviewed, and were rated concerning how frequently and how easy they were performed.

Software implementation

The implementation of the prototype aimed first of all at ensuring real-time interactivity with a 3D modeled environment. Operations on 3D objects should primarily be controlled by *direct manipulation* techniques, e.g. moving an object by dragging it around with the mouse (Ziegler & Fähnrich, 1988).

In order to deliver interactive 3D graphics, the prototype utilized the QuickDraw 3D API (Apple Computer, 1995). QuickDraw 3D (QD3D) is an object oriented API, i.e. it can retain 3D data within objects, such as, cameras, lights, transforms, geometry, textures, etc. Furthermore, QD3D supports hardware acceleration and a platform independent file format, named 3D MetaFile (3DMF). The target platform for this version of the prototype was Power Macintosh systems (Apple Computer Inc.).

The features implemented were, for instance:

- Multiple cameras. The camera connected to the active view was controlled by the keyboard arrow keys for controlling walkthroughs.
- Moving an object was performed either by direct manipulation or by numeric input. Any of an object's six degrees-of-freedom could be locked. Objects could also be linked together.
- Changing an object's width, height, and depth.
- Importing objects from a library.
- A metric distance could be obtained with a "measuring tape", dragged between two points.
- A "taking photo" tool was implemented for saving images, to later be used for print-outs or pictures in documents.

Usability test and evaluation

A usability study was performed in order to evaluate the prototype, with emphasis on using the fundamental operations. The study included two groups of representative future users: five OT students near the end of their education, and four disabled persons who all had major physical impairments. In the test, the subjects had to perform a number of basic tasks. None of the subjects had any prior knowledge or experience with this research project.

The study consisted of two test sessions (three weeks apart) and a final interview. Test session I started with a 45-minute standardized introduction of the program, in order to teach the subject how to use the program, and to ensure that all subjects had the same level of experience with the program. The subjects were then asked to carry out 12 specific tasks. Three weeks later, test session II was a similarly performed test. In this session, 9 specific tasks were given. After session II, the subjects were interviewed regarding their opinions on the usability.

The subject's performance was directly observed and video-recorded. The information gathered were:

- Success rate.
- Usage and error patterns.
- Task completion time.
- Error time.
- Number of times using quick reference card.

Conclusions

It was found that it is possible to realize a planning tool for environmental adaptations, both regarding usability and technical efficiency. The usability evaluation confirms our findings from previous case studies, regarding the relevance and positive attitude towards this kind of planning tool.

Although the prototype was found to be satisfactorily efficient for the basic tasks, the observations as well as the interview answers revealed several items to be improved or added in future prototype versions, such as:

- Add a "camera control panel", that supplements the keyboard-keys with graphic buttons.
- Give a visual hint on how the object will rotate before executing the operation.
- Support object rotation by mouse-dragging.
- Prevent that imported objects appear outside current view, or getting occluded by a nearlying object.

- Improve the measuring tool by drawing the line in a thicker and stronger contrasting color.
- Provide a “snap-to“ function for exact positioning of objects, e.g., to nearest centimeters or inches.
- Add on-line guiding for parts that caused the most problems.
- Create an undo-function for undoing a number of the latest performed actions.
- Implement standard editing operations, such as, cut, copy, and paste.
- Extend inputs for object properties such as, surface material, color, center of rotation, etc.

Regarding the learnability, it was found that the subjects satisfactory could use the program, based on the 45-minute standardized introduction. Subjects’ performance after the three-week pause showed slower performance times, increased percentage error time, and increased use of the quick reference card.

FURTHER PROTOTYPE DEVELOPMENT

The personal computer market is at present largely dominated by Intel-based computers and the operating systems of Microsoft Corp. With the releases in 1995 of the operating systems, Windows 95 and Windows NT 4.0, there are now rather few differences in the user-interface between Macintosh and Windows systems. Since they now both are fully making use of the desktop metaphor and the techniques of direct manipulation, it has become harder to find specific advantages that motivate exclusive development for a Macintosh platform.

Therefore, after the Macintosh-version described in Paper V, the decision was made to transform the code to the Windows 95/NT platform. Since the QD3D API in 1996 also was supported on Windows 95/NT, and since the Magrathea code was modularly designed with a future porting in mind, about 50% of the code could be directly re-used. The largest programming effort was needed for the interface parts, which had to be completely re-written in order to work on the Windows platform, and to be consistent with other Windows applications (Kucer, 1998).

Although the QD3D API was entirely supported on Windows, there were unfortunately no 3D-accelerator cards released for PCs that could support this API. Hence, the interactivity would be seriously limited, even for 3D models with low complexity. In order to overcome this limitation, the possibility of creating a *plug-in renderer*[8] was explored. A plug-in renderer was developed that could translate the rendering information into the *OpenGL* format. OpenGL is today perhaps the most common 3D

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[8] the plug-in architecture is a feature supported by the QD3D API in order to let models be rendered through alternative renderers from third-party developers.

graphics API, enabling a high flexibility and rendering quality, and many 3D-graphics card are able to accelerate through this API. It was found, however, that although the rendering quality was greatly improved, the increase in speed was not particularly significant. One reason may be that the translation process requires some calculation power. Another reason was that given the plug-in architecture, the OpenGL calls were difficult to optimize.

Instead, in order to ensure the fastest possible rendering speed for the Windows platform, Magrathea was supplemented with the ability to retain a 3D model not only in the QD3D format, but also simultaneously in the *Direct3D* format. The Direct3D API (Microsoft Corp.) is supported on Windows 95/98, and today most consumer-oriented graphics card developers have optimized their 3D acceleration for this API.

Conclusively, the current Magrathea prototype under investigation has the following features:

- Runs on the Windows platform.
- Similar functions as the Macintosh version are supported, but the interface solutions differ, mainly for better fitting into the Windows environment.
- New features (as compared to the Macintosh version) are mainly: (i) direct manipulation of object/segment rotation; (ii) a camera control panel with graphic buttons for controlling camera motion; (iii) clipboard functionality (cut, copy, paste); (iv) extended control of object properties, such as, surface material and color; and (v) control of light-sources and ambience properties, such as, intensity and color.
- Ability to select among various rendering methods: (i) QD3D software renderers; (ii) Plug-in renderers, such as, the OpenGL translator, or perhaps a non-interactive ray-tracing renderer; or (iii) Direct3D rendering for the most optimized rendering speed.

Figure 3 illustrates the interface of the PC version of Magrathea.

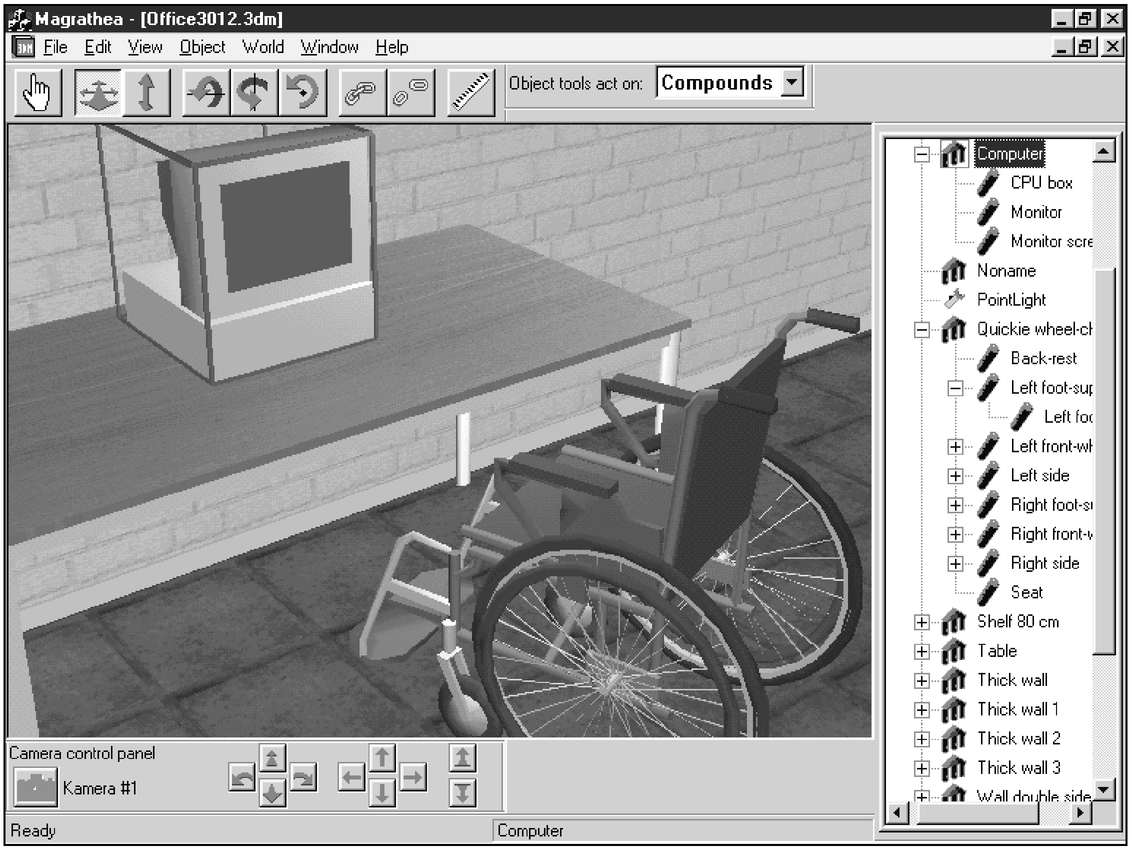

Figure 3. The interface of the PC version of Magrathea. The main window shows a view through the chosen camera. Below to the left, a button-panel enables direct control of this camera. A selected object (in this case, the computer on the table) is indicated with a red bounding box. To the upper left, the horizontal toolbar contains buttons for selecting, moving, rotating, linking, and un-linking objects and segments; and measuring distances. To the right, the object browser window presents the hierarchical structure of objects in the current 3D model.

3. MANIKIN ANTHROPOMETRICS AND BIOMECHANICS

As previously discussed, a future planning tool must support the use of *manikins* (i.e. computer models of humans). A manikin could be used to visualize and test various aspects of man-environment or man-machine interactions, and manikins can also be used to evaluate workloads using biomechanical calculations.

As earlier mentioned there are several commercial, highly sophisticated manikin systems available today. But unfortunately, it would be difficult to integrate such systems with the planning tool here prototyped, since the manikins may only be used within a specific CAD package and/or platform, or they can only be used as a stand-alone application. Furthermore, the licenses of these packages are often very expensive.

However, recent development in 3D graphics hardware and software for the consumer market has opened up possibilities for a broader range of low-cost applications, and manikins are now also found in a wider spectrum of applications, for instance, in 3D modeling/animation packages, and in games.

Unfortunately, the information needed for designing manikins with a high anthropometrical and biomechanical fidelity is still scattered, and in some areas incomplete. Therefore, some extrapolations or estimates have to be made by designers of manikin systems. Another problem is that system designers do not always report their sources of anthropometric data sufficiently, and/or how their own estimations were performed. As a result, there can be many difficulties with assessing the validity of biomechanical results, and with making comparisons between different systems. Attempts are made, though, to obtain a general agreement about manikins and analysis principles. The European Committee for Standardization (CEN) has initiated a project, TC 122, with the aim of forming a basis for the standardization of the structure and characteristics of computer manikins (Örtengren, 1992).

With the objective to provide a system independent support for the design or modification of manikins, Paper VII reviews some frequently cited published anthropometric and biomechanic data, and present a uniform segment-by-segment compilation. The compilation of data has been implemented as a manikin "template" document, with the use of a spreadsheet program (Mircosoft Excel). Intended areas of application are primarily within a 3D graphics context, either when designing/modifying manikins using an existing 3D modeling/CAD package, or when developing new programs that will support manikins.

One major difficulty in completing a detailed and consistent manikin database (as exemplified in Paper VII), is that large parts of the required measurements do not exist in literature. Instead, one often must settle with extrapolations and approximations. However, *in vivo* techniques, such as, radiography, computer tomography (CT), magnetic resonance imaging (MRI) and ultrasound, are becoming more and more accessible and cost-effective, and one may anticipate more anthropometric and biomechanic studies using these techniques.

Paper VI presents *in vivo* measured biomechanic data of the neck-shoulder region, where the measurements were based on MRI. Previous biomechanic data for the neck-shoulder region were sparse and mainly based on cadaver studies. The results may for instance, be used in further refinements of manikin databases, such as, the one presented in Paper VII.

SUMMARY OF PAPER VI

Introduction

An MRI study on healthy Scandinavian female volunteers, was performed to provide *in vivo* measurements of the neck-shoulder region, with the objective to providing data for more detailed future biomechanical models and computer-based manikins. A magnetic resonance scanner was used to capture the inner anatomy, together with the measurements of some standard anthropometric dimensions.

This paper presents data of the linkage system of the upper spine, such as, link lengths, link rotations, antero-posterior endpoints of the spinous process, and also the correlation between link lengths and anthropometric measurements. A sub-study will investigate possible differences in link length and link rotation between non-flexion and maximum-flexion of the neck. Furthermore, there is an assessment of how geometrical errors of the MRI scanner affect the results.

Method and materials

The study involved 20 Scandinavian female volunteers, aged 22-58 years. Their occupations were typically clerks, administrators and students. The subjects did not at the present time, or in recent years, have any pain or disorders in the neck or shoulders.

Image acquisition was carried out on a Siemens Magnetom Vision 1.5 T whole body MR scanner. In order to optimize the signal-to-noise ratio in the investigated areas, all measurements were performed using a cp-spine-array coil.

Local magnetic field inhomogenities may result in an erratic signal distribution, primarily in the outer edges of the field-of-view, which may cause errors in distance and area measurements. To investigate the geometric uncertainties, a phantom was designed, consisting of a plastic tube filled with a water-solution, and with plastic pins intersecting the tube at some reference positions.

The main errors in the results were assumed to originate from two factors: (1) the geometrical uncertainties of the scanner, which was estimated by the use of the phantom. (2) the precision of the manual localization of the landmarks from the images, which was investigated by comparing results between two repeated measurements.

Results

Presented data concerned anthropometric measurements, as well as anatomical measurements: link length, link rotation, and antero-posterior endpoints of the spinous process.

Correlation coefficients were calculated between the link lengths. These correlations generally tended to increase the closer two links were to each other. Regarding correlation between link lengths and the anthropometric values, height measurements - especially sitting height and stature - correlated better than weight, circumference, and breadth. Linear regressions were calculated for estimating link lengths using stature as a predictor.

Differences in link lengths between non-flexion and maximum-flexion of the neck were mainly below 1 mm, and hardly detectable using these images. For link rotation, the differences were largest for the links of the 5th cervical vertebra through the 1st thoracic vertebra.

Tests with the phantom for assessing geometrical errors caused by the scanner revealed that such errors had minor influence on the results, and it would be fairly safe to disregard these errors.

The differences between the repeated measurements were significant for the links of the 1st and 2nd cervical vertebrae. For the remaining links, the differences were smaller, and were not significant.

Conclusions and discussion

The measurements in this work provide kinematic data for the upper spine, which are primarily intended for rigid linkage models, especially where a linkage-refinement level of one link per vertebral body is of interest. The reported kinematic data of the upper spine was based on images in the sagittal plane. This data may in the future be supplemented with measurements on cross-sectional areas, volumes, and moment arms for different muscles, obtained from the transversal images of the neck, also acquired in this study (to be presented in a future paper).

There are several advantages of using MRI in biomechanical studies since it offers a unique accuracy and contrast for soft tissues, such as, muscles, tendons and ligaments, viewed on living subjects (Tracy et al. 1989; Wood et al. 1996). At present, however, MR scanning is relatively expensive and its accessibility may be limited on many locations. Compared with X-ray methods, MRI has the advantage of not emitting any ionizing radiation. The MR method is therefore satisfactory from an ethical point of view by avoiding radiation exposure on healthy volunteers. On the other hand, radiography images can be acquired more rapidly, which is for instance, beneficial when investigating the variation of joint-positions during flexion/extension of the spine (Pearcy et al., 1984; Ogston et al., 1986; Roozmon et al., 1993).

This study is confined to Scandinavian females, and in future work it would be of interest to gather similar information for the male population. It would also be interesting to compare the present results on a healthy population with a similar study on individuals with neck/shoulder disorders caused by work-life exposure. In further biomechanic/anthropometric studies one may also investigate the potentials of comprehensive improvements of the MRI-technology, such as, rapid 3D acquisition, and sequential acquisitions for certain body movements.

SUMMARY OF PAPER VII

Introduction

With the objective to support the design of manikins, this report reviews and compiles published anthropometric and biomechanic data into a uniform three-dimensional nomenclature. The general strategy was to compile the data into a segment-by-segment form, in order to match an object-oriented programming technique and modern 3D graphics APIs. Hence, a manikin is described with a varying number of segments, which retain information on size, weight, center-of-rotation, link length, degrees of freedom, joint range, center-of-mass, moment of inertia, etc.

The compilation of data was to be implemented as a manikin "template" document, with the use of a common spreadsheet program (Mircosoft Excel). Intended areas of application were primarily within a 3D graphics context, either when designing manikins using an existing 3D modeling/CAD package, or when developing new programs that will support manikins. Certainly, there also existed the opportunity to use the template as is, with no specific modeling or application development in mind.

Methods and techniques

The measurements and relations in the spreadsheet template were as much as possible based on available data and underlying assumptions that are present in the literature on anthropometrics and biomechanics. Parameters of interest concerned: anthropometric dimensions, body linkage, inertial properties, geometry, and range of joint motion.

Anthropometric dimensions: To make complete anthropometric tables covering several sub-populations, and a fixed set of body dimensions, it is often necessary to combine the results from different sources. Using the ratio-scaling technique, all body dimensions were presented as values of the coefficients E_1 and E_2, defined as:

$$E_1 = \frac{\text{mean of dimension}}{\text{mean of stature}}$$

$$E_2 = \frac{\text{standard deviation of dimension}}{\text{standard deviation of stature}}$$

Body linkage: The kinematics was simplified into a rigid mechanical system. Each segment was provided with its own local coordinate system, a frame, which constituted the reference point for the other spatial parameters of that segment. The frame's origo was located where the segment has its proximal joint (for the extremities) or caudal joint (for the trunk). The term "link" was defined as: starting at the segment's center of rotation, and ending where it was adjoined with its son segment. Each segment contained exactly one link.

Inertial properties: Each segment were provided with the following inertial properties: mass, center of mass, and moment of inertia.

Geometry: The geometric representation of the segments was only described with a "bounding-box", i.e. the smallest rectangular box that can encompass the geometry. The midpoint of the box, called the center of geometry, was represented as a 3D coordinate in the segment's frame-space. The centers of geometry were estimated to match the body linkage with the anthropometric measurements.

Range of joint motion: Each segment was presented with three Euler angles, which all were set at zero for the default body posture (standing upright, face forward, arms hanging down with thumbs directed forwards). Each Euler angle had minimum and a maximum value, delimiting the rotational range.

Design of the spreadsheet template

The spreadsheet template was implemented as an Excel (Microsoft Inc.) document, retaining the following types of pages:

The manikin personalization page contained input fields for characteristics that were needed for creating a new manikin. The characteristics were name, sex, ethnicity, geographic region, stature, weight, and general joint mobility. The stature could either be specifyed as a percentile, or as a direct measurement. For the weight, there was a choice of either entering a Body Mass Index value, or entering a measured value.

Three subsequent pages presented intermediate results. The first page, contained the anthropometric dimensions calculated from the E-coefficients. The second page contained link length estimations of the major links. The third page contained the calculated joint-ranges.

The segment properties were presented on four separate pages. Each page described a certain level of complexity, i.e. the number of segments in a manikin. The segment properties were retained in tables with columns for: segment name and its position in hierarchy; frame offset; frame orientation; minimum values of the joint-range; maximum values of the joint-range; link length; bounding box size; mass; center of geometry; center of mass; principal moment of inertia; and radius of gyration.

The last page was a data reference for calculations of the E-coefficients. The page contained coefficients for 27 anthropometric dimensions for 40 different populations, categorized by geographic location and sex.

Discussion

In order to ensure platform independence and a maximum flexibility for future improvements, the spreadsheet template was kept as "raw" as possible, meaning that the use of macros or scripts were avoided. The intention was that future improvers should find the template open and straightforward for changes and additions. Unfortunately, the support for guidance and error-handling was therefore sparsely implemented.

The major difficulty in completing a detailed and consistent manikin database is that large parts of the required measurements do not exist in the literature. For now, one have to settle with more or less satisfactory approximations, while awaiting supplementary studies.

The current spreadsheet implementation has clearly numerous limitations, as for instance: it applies only to adults in a range of about 20-50 years; "normal" body build and body functionality are assumed; and that heel-heights, clothing weight, and clothing thickness are not included in the calculations. Future improvements should address a broader range of somatotypes, perhaps by using more sophisticated predictions methods than the E-coefficients. Future improvements should also better support the design of manikins of the elderly, children, and people with disabilities.

4. CONCLUSIONS AND DISCUSSION

The participants of the planning and design process of environment adaptations may have large differences in previous knowledge and experiences. It is therefore important that information is given sufficiently and understandable, so that everyone can take an active part in the process. Otherwise, there is an apparent risk that discussions will be kept among the experts due to difficulties in the understanding of complex and technical adaptation issues. A series of planning sessions where people can communicate and forward suggestions on equal terms would not only be essential to obtain a well functioning and widely accepted solution, but also to influence the rehabilitation process positively by encouraging the end-users to have an active role.

It was found that a planning and design tool, as prototyped in this thesis, can be used in a planning group to support understanding and active participation among different kinds of participants. It also makes it possible for a professional planner, such as an OT, to make designs of future environments and evaluate the functionality with high accuracy. To benefit from an iterative planning process, it is important that all the people concerned can attend through the whole process. For homes, it may be important to include relatives, construction engineers, and home-service personnel. For workplaces, management and colleagues must be represented.

The proposed planning tool has evolved through several prototype stages: from the assembly of mainly commercial software to a self-developed program for 3D model interaction. Today, the prototyping strategy is a common and widely acknowledged approach in computer system design, where the development can be regarded as an iterative process (Gould, 1988). A prototype can emulate the interaction of a system that has not yet been implemented, and is especially appropriate for complex systems that demand a high rate of human-computer interaction (Dix et al., 1993).

The performed case studies provided the means for an user-centered prototyping process. Involving prospective users in a prototyping process can make it possible to evaluate the system at an early development stage, which provides high validity regarding needs and requirements. A user-centered approach can be considered as a shift into focusing on human learning and communication, and adequacy in practical use, rather than on the fastest development or the most efficient program code (Ehn, 1988).

With the developed and evaluated Macintosh-based version "Magrathea", it was found that it would be possible to realize a planning tool based on ordinary personal computers, regarding both *usability* as well as *technical/economical efficiency* (although the usability test revealed several necessary improvements of the current prototype version). With such a tool, one would be able to perform tasks, such as:

- selecting construction elements from a 3D object library, such as, modules of walls, doors, and windows, and assembling them into one or many rooms.
- bringing in furniture, or other equipment of interest, and creating different interior arrangements.
- manipulating manikins for testing ergonomic aspects such as, reach, clearance, accessibility, etc.
- rearranging and exploring different suggestions during planning sessions.

Further evaluation of the prototype, and studies on how it can be used in a planning process, may be conducted similar to the last phase proposed in the case study design in Paper III: The OTs themselves use the software in an extent they think is appropriate. The OTs would also be responsible in documenting the observations. Thereby, no external researcher needs to take part in the planning sessions. The involvement would instead be limited to consultative support (such as, assisting in 3D modeling), and to interview the participants before and after the planning process.

An important feature in the planning tool would be the integrated support for manikins, since the design of environments for physically disabled people can involve numerous critical man-environment aspects to be considered, e.g. wheelchair accessibility, reach abilities, positioning of handles and handrails, etc. The manikins should be anthropometrically valid, and as well as possible represent the mechanical behavior of humans. The latter need to be traded off with simplicity in manipulation, though. It is also important that the manikins are flexible for adjustments to an individual's size and physical abilities/impairments.

The manikin spreadsheet template was developed in order to aid the design and modification of manikins. The compilation of data was based on commonly referenced anthropometric and biomechanic data, and structured in a segment-by-segment form. This data reference may be utilized directly in its current template form, or to be integrated into future manikin-featured applications.

Unfortunately, all the data required to complete such a manikin data reference, with a satisfactory level of accuracy, can not entirely be obtained from the literature. In many cases either one must rely on extrapolations or approximations, or one must conduct new anthropometrical or anatomical research.

In recent years, the development of computer-based tomography techniques, such as, computed x-ray tomography (CT) and magnetic resonance imaging (MRI), have made it possible to perform measurements on living subjects. Thus making it possible to supplement/refine available biomechanical data without many of the problems associated with cadaver studies. In order to obtain data on musculoskeletal properties of the neck-shoulder region, an MRI investigation was performed on Scandinavian females. These measurements can be used for improved biomechanical modeling, as well as for further refinements of manikin specifications, such as the spreadsheet template described in this thesis. In the future, one may look forward to an extensive use of *in vivo* measurements with improved tomography techniques, aiming to further supplement the data needed for biomechanics and manikin design.

A time-efficient usage of a planning tool would be dependent on the existence of a large 3D object library, consisting of objects, such as, construction elements, furniture, office equipment, wheelchairs, etc. However, one can never expect that the library covers more than a fraction of all the furniture/equipment available on the market. To maintain an object library, as well as to aid therapists in modeling special furniture or equipment, probably requires a support organization. Such an organization may also be responsible for technical support and training therapists.

Another concern about a large 3D object library is that the 3D objects may originate from various modeling/CAD programs, and it is therefore important to have consistency in file format, scale, level of detail, etc. Regarding the selection of file format, the 3DMF format has proven to be comprehensive, flexible, and platform independent. The capacity to define custom attributes has been useful for retaining various manikin parameters, for instance. Unfortunately, the 3DMF format has been sparsely spread on the Windows 95/NT platforms. In the future, it may therefore be necessary to re-evaluate which format an object library should be retained in. Other candidates would be VRML[9] (Ames et al., 1997), DirectX (Microsoft Corp.), or the 3D Studio format (Autodesk Inc.).

One of the critical technical factors in the past was the requirement on rapid 3D rendering in order to obtain an interactive manipulation of 3D objects. By utilizing today's 3D accelerator cards, such systems requirements can be met, both on Macintosh and PC computers. However, the frame-rate is far from dependent on system performance alone. The number of objects put into a world also significantly affects the frame-rate, and future users need to be aware of this. One may have to recommend not retaining more than a few fully equipped and furnished rooms or one single apartment within a document. Of course, the fewer details the object has, the more objects can be put in the document. It is therefore important that providers of object libraries offer objects with an appropriate balance between realism and complexity. The use of textures can, for instance, enhance the perception of depth (Todd & Akerstrom, 1987). This is especially useful on large, plain objects, such as, walls and floors. However, since a large number of textures puts greater demand on the hosting system, a future object library may have to supply objects in two versions: one that is complex and textured for high-performing systems, and another that is less detailed and non-textured.

Since one may anticipate a continuos increase in 3D graphics performance on consumer-oriented computers, there may in the future be more headroom for extra computation running simultaneously with the real-time rendering. So far, implementing such features have been avoided since it may have decreased the frame-rate too much. A behavior that would enhance the sense of reality when interacting with the 3D models

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[9] Virtual Reality Modeling Language

is *collision detection,* i.e., a moved object should automatically detect and indicate a collision with another object, thus keeping objects from intersecting. Another desired feature is *gravity*, i.e., an unattached object should automatically fall down onto the nearest underlying object, or to a ground-level. Biomechanical calculations of work-loads may also be implemented in the future. The file structure of Magrathea was in designed in correspondence to the manikin spreadsheet template, meaning that a manikin in this program can retain similar parameters as dealt with in the spreadsheet. Thereby, it would be fairly straightforward to, for the least, implement simple static calculations for each joint of the upper body, such as performed in the previous "BioMek" program.

The great advantage with immersive Virtual Reality equipment is that it can enhance the sense of presence and the means to interact with a 3D modeled environment. The disadvantages may still be their expensiveness and that they can not easily be moved from the lab-environment. Portability can, for instance, be dependent on the tracking system and/or the presentation system of choice. Another concern, especially regarding this field of application, is that such a system should preferably allow two (or even more) persons to act simultaneously inside the virtual environment. Today however, there exist VR systems that can support such a collaborative interaction. The CAVE system, for instance, allows several people to stand in a room with surrounding projection of the virtual environment (Browning et al., 1993).

The rapid technological development for the past 10 years has not merely resulted in continuously faster and cheaper computers, but it has also affected how we use, and how often we use computers. In Sweden today, many people have access to computers, as well as to the Internet. This development will, of course, also affect the use and availability of a future planning and design tool in the area of environment adaptations. Applications for collaborative design over the Internet, for instance, is existing already today, and with an increased bandwidth of the information channels, it may soon be commonly feasible. The Internet would also be the ideal medium for the distribution of a 3D object library.

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