VIRTUAL REALITY FOR A HUMAN-CENTERED DESIGN METHODOLOGY

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Abstract

Simulation tools, which are set in Virtual Prototyping (VP) techniques, have been implemented in recent years in engineering design fields, such as in industrial design, manufacturing, maintenance, reliability or ergonomics. Concerning the human factor, by studying product or workplace, engineers can forecast usability problems by means of 3D human model simulation. Indeed, these simulation tools offer great possibilities for designing and evaluating product usability features. However, they also meet drawbacks such as a lack of interaction and of immersion with the Digital Mock-Up (DMU). Now, thanks to Virtual reality (VR) engineers can have sensory-immersion and high interaction level with the DMU during the whole product design process. It makes it possible to solve problems that can not be detected with a 3D human model. In this context, our research interest is Design For Usability (DFU) methodologies based on VR and their impact on product or workplace design process. Our goal is to provide methods and simulation tools for product usability definition and optimization. Based on a review of current VR applications for usability studies, we present our method for integrating VR technique in a human-centered design process. Thus, we introduce "Virtual Reality Aided Design for Use" which consists in three overall VR design tasks that can be performed in product design process. We apply a 3D digital human associated with parametric CAD models and a virtual reality platform to the design process.

Keywords: Virtual Reality, simulation tools, manufacturing systems, mechanical engineering, human factors.

Presenting Author's biography

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1 Introduction

Today, the economic environment is characterized by weak growth and strong competition which incites companies to reduce deadlines, to decrease prices and to improve product quality. In this context, designers underestimate some factors such as ergonomics. The result of this is that many products which surround us have not been designed to be a response to end-user expectations, such as the need for "usability" [1]. Usability represents the facility of use of a product. Indeed, it corresponds to the capability of the technical device to be used easily, by a given person, in order to achieve the task for which this object was designed [2]. We come across products intended for the general public, which remain complex and unsuitable. Workplaces, which are part of manufacturing systems, are also inadequate and cause serious health problems. This lack of human-factor consideration in the design process is thus one of the multiple causes of occupational hazards/injuries and particularly for the most known which is "Repetitive Strain Injury".

Thus, companies must change their design process and integrate the human factor into their procedures in order to stay competitive and innovative. An answer can be found in Design For Usability (DFU) [3] or Design For Ergonomics (DFE) [4] which are set in Design For X (DFX). Indeed, DFX is a succession of product development techniques which can effectively be applied to the design process. It allows not only the rationalization of the products, but also the associated processes and systems [5]. In this context, we have witnessed the rise to power of Virtual Prototype which is a well accepted solution to forecast usability problem in design process. A virtual Prototype can be defined as below: "Virtual Prototype, or digital mock-up, is a computer simulation of a physical product that can be presented, analyzed and tested from concerned product life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called Virtual Prototyping (VP)" [6]. During usability studies, designers usually apply 3D human model (or virtual operator) simulations. These simulations enable them to develop and evaluate ergonomic aspects of the Virtual Prototype [7]. For instance, they are able to assess clearances, reach, visual requirements, and postural comfort at the earliest design stages. Figure 1 shows a digital human model called MANERCOS resulting from our development [8]. This enables the designer to incorporate features into design that minimize the risk of injuries before a person ever physically encounters the workplace. This solution gives good results in design for use and evaluation of the results [9]. However, some shortfalls still remain. We can quote, for example, interaction and immersion needs or compatability problems between 3D CAD models and the 3D human model. Virtual Reality (VR) tools offer a means to solve these problems.

Fig. 1 An example of virtual human: reach volume study with MANERCOS

Indeed, VR can be defined as a human-computer interface which brings a real-time sensory-immersion and interaction with a virtual environment (VE). In fact, many works suggest VR could be a powerful assistance tool in human-centered product design and particularly with ergonomics integration [10], [11], [12], [13], [14], [15]. However, in spite of the obvious complementarity of VR and VP for working on human-factors the work met on this subject is too often specific. VR is also often applied without real links with product design and development phases [16]. It should be integrated in a more structured way [17]. Our objective is thus to provide a methodology that can organize and link different VR design tasks associated with workplace use definition.

In the second part, we present a literature review of VR applications in the ergonomics field during a design process. Based on this review, we introduce, in a third part, a methodology for VR techniques integration in a human-centered and collaborative design process. Our proposal introduces "Virtual Reality Aided Design For Use" (VRADU) based on three global design tasks which can be achieved with VR techniques.

2 Human factors and virtual prototyping applied to manufacturing systems

This chapter deals with VP in human-centered design process. We present the limitations of 3D human model simulations drawn from our experiment in design cases. Then, we present theoretical applications of VR techniques in ergonomic studies and we show in a third part the potential design phases concerned by these applications. We conclude with several research hypotheses.

2.1 Lack of interaction on the Virtual Prototype with 3D human model simulations

The simulations carried out using 3D human models have enabled us to obtain ergonomic evaluation

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results (postural score, lift score, etc.) and 3D animation or pictures representing workplace use. These results are used in projects reviews with all team project members (engineers, ergonomicists, product end-users, etc.). So, the communication medium during these meetings is paper or animation/picture visualization. The main problem encountered with these standard simulations is the lack of interaction offered to designers. We can develop this idea at three levels.

At the first level, during industrial projects carried out using a 3D human model, team project members want to be able to exceed simple viewpoint exchanges about work simulation activities. At a minimum, they required the improvement of the conditions of simulation observation and comprehension of results. This would enable more criticisms on the suggested solutions. Moreover, once project reviews have been carried out, CAD model modifications still remain to be made. Indeed, the modifications required are made on a CAD station but without direct link with the simulation tools used.

At ergonomicist's level: the main reported reproach is that he is not able to replace the digital manikin as if he was in a real situation. Indeed, the ergonomicist needs to "feel" workplace constraints, a configuration which is impossible with a standard 3D manikin. Moreover, the use of the virtual human reaches its limits when we want to take into account the concept of each user's specific experiment. It's difficult, and even impossible, to consider it during simulations. It is thus almost impossible to evaluate the way that the real operators would react, with all his work practices. All in all, the ergonomicist would like to put a real operator using the Virtual Prototype in the evaluation loop.

At the third level, sometimes we notice that the users have difficulty submitting negative criticisms about numerical manikin proposed simulations. Indeed, in certain cases, the operators are rather "in admiration" in front of the 3D videos or pictures. Moreover, the user encounters difficulties to feel himself "as if inside the manikin" and to forecast usability constraints. Thus he omits problems which will be identified only with the physical mock-up (PMU) construction.

2.2 Virtual reality and ergonomics applications in the design process

VR applications in the ergonomic domain are numerous and it would be too difficult to give an exhaustive list of them and moreover they are often specific [16]. However, we can sort four levels for VR contributions in ergonomics: activity assistance, training, work analysis and tools or new work activities design [13].

Activity assistance requires the distinguishing of two assistance types which are: assistance linked with usability defaults and task assistance. The second one is a more developed research field and [13] defines three applications for this assistance:

• Information enrichment: it is possible to bring, for example, more detailed information to the operator by giving a more understandable explanation of information which can be outside the operator's experience.

• Automation of certain actions: it gives also the possibility of automating some actions necessary for task achievement.

• Information and whole or part action filtering: it allows limitation of the environment risks and complexity. This assistance can be an information filtering process or a restriction of the range of actions left with the user.

VR training applications consists in developing a virtual training environment which can be used by operators or by the trainer. The first is presently more widespread. Its advantages are: the motivation brought by the attractive aspect of VE; greatest realism, means of approaching reality without risk and at lower cost; the use of impossible modes of interactions in the physical world [13].

Activity analysis can be justified when it's impossible to access the real situation or when the concept, tasks or situations which are to be evaluated, do not yet exist. It's mostely due to the current state of research which does not enable the guarantee that there is an effective transfer between the data collected by VR analysis and the real situation [18] [19]. However, it's important not to underestimate interaction device limits. These difficulties in achieveing a good interaction are counterbalanced, compared with a Physical Mock-Up (PMU) by the following advantages: lower costs, restricted obstruction, portability and flexibility, the ubiquity and nonexistence of temporal or geographical dependence.

VR can be of a great interest in ergonomics when it's used as an assistance tool for product or work activity design. VE gives an alternative to the specific representations offered by CAD tools or paper drawing as regards visualization and communication between various actors of the design process. Other applications can be feasibility studies or potential problem detection on proposed concepts. It permits choices to be made between several design solutions. For instance, it can be used in ergonomic analysis for mountability and maintenability tasks [20].

2.3 Virtual reality and product design

One unique product design process accepted and used by everyone does not exist. In engineering design, several works propose various design process modeling methods. However, we use a model which describes design process based on four stages: feasibility studies, preliminary studies, detailed studies and industrialization [21].

Feasibility studies serve to identify the need, to study the market and the design project feasibility. The need is thus translated in a final document entitled "functional specification". The preliminary studies combine the search of ideas with creativity. They lead to several solutions represented with sketches, drawings and numerical models. It also includes technical solution research. The detailed studies validate, optimize and industrialize the design solution chosen. The industrialization stage enables "design-evaluation-validation" loops of the final prototype with potential users to be carried out. These evaluations bring additional information related to the implementation of the product and the safety of use.

A literature review shows that many VR applications are possible during the whole design process but there are few works which describe VR integration in the product design process and even fewer in a human-centered one. We can nevertheless quote [22] and [15] that describe some recent works about structured approaches. To sum-up, VR techniques take place at all design stages for various applications such as developing human factors or ergonomics. We can call these applications "virtual reality meeting points" between product design and related disciplines, as shown in figure 2.

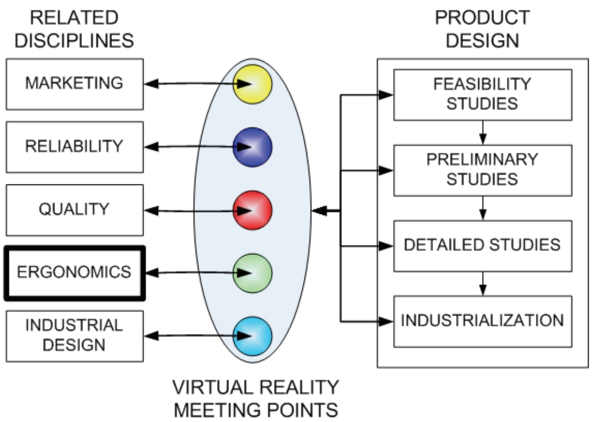


Fig. 2 Virtual reality and product design integration

3 Research Hypothesis

Our first hypothesis is to provide a human-centered design methodology which can bring innovation while designing usability feature in a more interactive and direct way. This consists in integrating, in a structured way, VR techniques in a collaborative and simultaneous design process.

A second hypothesis consists in improving ergonomic simulation integration in the design process with VR tool simulation. In this way, we will propose a more direct and interactive means for product usability definition.

The last hypothesis deals with the collaborative aspect of design. Thus, we propose to enhance 3D human model simulation understanding with VR techniques. It will enable us to have a better understanding of results obtained with 3D human models and thus to improve the collaborative work in design teams.

The next paragraph introduces our methodology called "Virtual Reality Aided Design for Use". We have applied several stages of this methodology during many industrial projects using our VR platform. As shown in figure 3, this platform has: 3 active stereoscopic screens, motion tracking devices, data glove, 3D sound devices, etc.

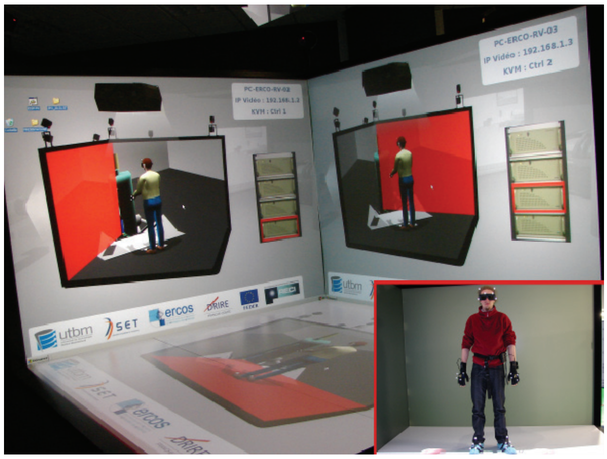


Fig. 3 Virtual reality platform

4 V.R.A.D.U: Virtual Reality Aided Design for use

Our human-centered methodology proposes the integration of the ergonomics field into product design by the intermediary of "use" definition. To do so, we introduce four stages which are carried out concurrently with design ones, as shown in figure 4. During "use analysis", observations and analysis of existing use and work situations are carried out. That gives criteria which will be added to the "functional specification". Then, the next stage consists of "use definition" starting from the solutions proposed during "preliminary study". 3D human model simulation makes this possible. "Use optimization" is focused on the selected solution which is given by "detailed study". Finally, observations are made and analysis is carried out on the new product.

Thus, we propose to link every stage of the ergonomics work to the product design using VR tools. "VRADU" method is composed of three global steps: "Product usability analysis with VR tools", "Product and related use ergonomic evaluations with VR tools" and "Product and related use design with VR tools" (figure 11). It involves all the design team members but for use definition, we make a focus on engineer, ergonomicist (human factors expert) and operator (real user). We define two kind of role for each one. They can be design actor or simply observer. A design actor has sensory-immersion and can interact with the Virtual Environment; whereas an observer has only sensory-immersion. We can also make a difference with the interfaces which are manipulated by the design actor or the observer. Each step can be separately achieved but they all contribute to product and use design process.

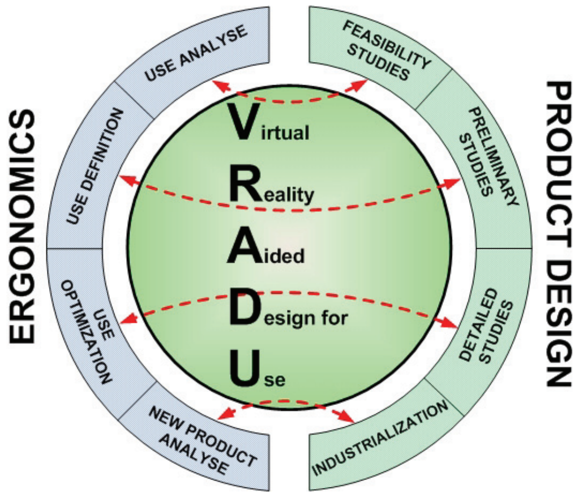


Fig. 4 Virtual reality and product design integration

4.1 Product usability analysis with VR tools

All project team members are observers. We have distinguished 3 different tasks that can be performed by the participants (figure 8). "Study and visualization of contextual assistances related to the product and its use" step consists in the product visualization associated with contextual assistances when we need some. For example, we can select a workplace element and see information about its usability function (figure 5).

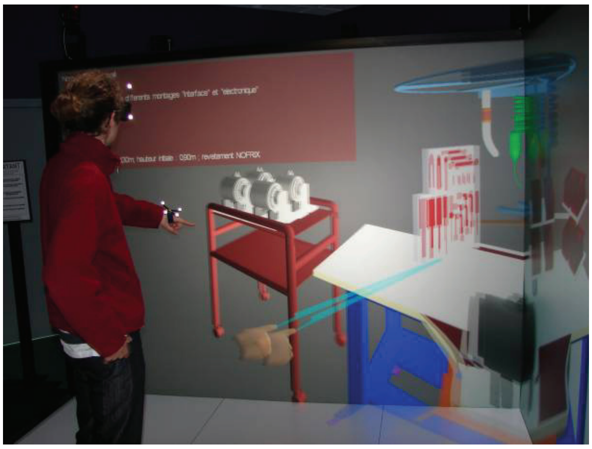


Fig. 5 Ergonomic evaluation for a lifting task simulation in VE

"Observations of 3D human model simulation" and "Ergonomics results from 3D human model simulation observation" steps allow to enhance 3D human model simulations thanks to VR tools immersion aspects. Project team members can visualize 3D animations and ergonomics results associated, as shown in figure 6.

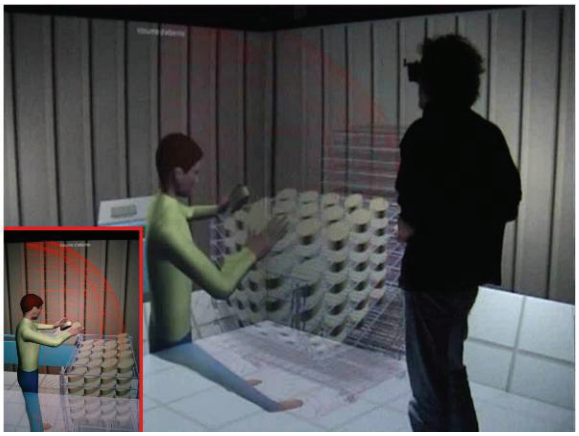


Fig. 6 Visualization of a 3D human model simulation and a reach volume analysis (without stereoscopic vision)

During these VR project reviews, team members can communicate among 3D human model simulation more easily than with classical communication medium. They can exchange viewpoints about the product use and propose modifications on the virtual prototype.

4.2 Product and related use ergonomic evaluations with VR tools

At this stage, the operator is more active and takes a design actor role. Indeed, he can interact with the virtual prototype and simulate the product use. Concerning the ergonomicist, he takes an observer role. He manages the ergonomic simulations and evaluations. Our first results focused on physical ergonomics aspects help us to define three VR tasks: "Use simulation with a real operator", "Usability normative evaluation with a real operator" and "Usability organizational evaluation" (figure 8).

During the product use simulation, the operator can have an immersion in the future workplace. Then, the ergonomicist can realize normative evaluation based on ergonomic tools and method such as lift evaluation, postural workload evaluation as shown in figure 7. He can also achieve organizational evaluation during the product use.

Fig. 7 Ergonomic evaluation for a lifting task simulation in VE

At this stage, these ergonomic evaluations give a more detailed and quantitative modifications list. The designer's objective is to directly apply these modifications to the native CAD model, which constitutes the goal of the next stage.

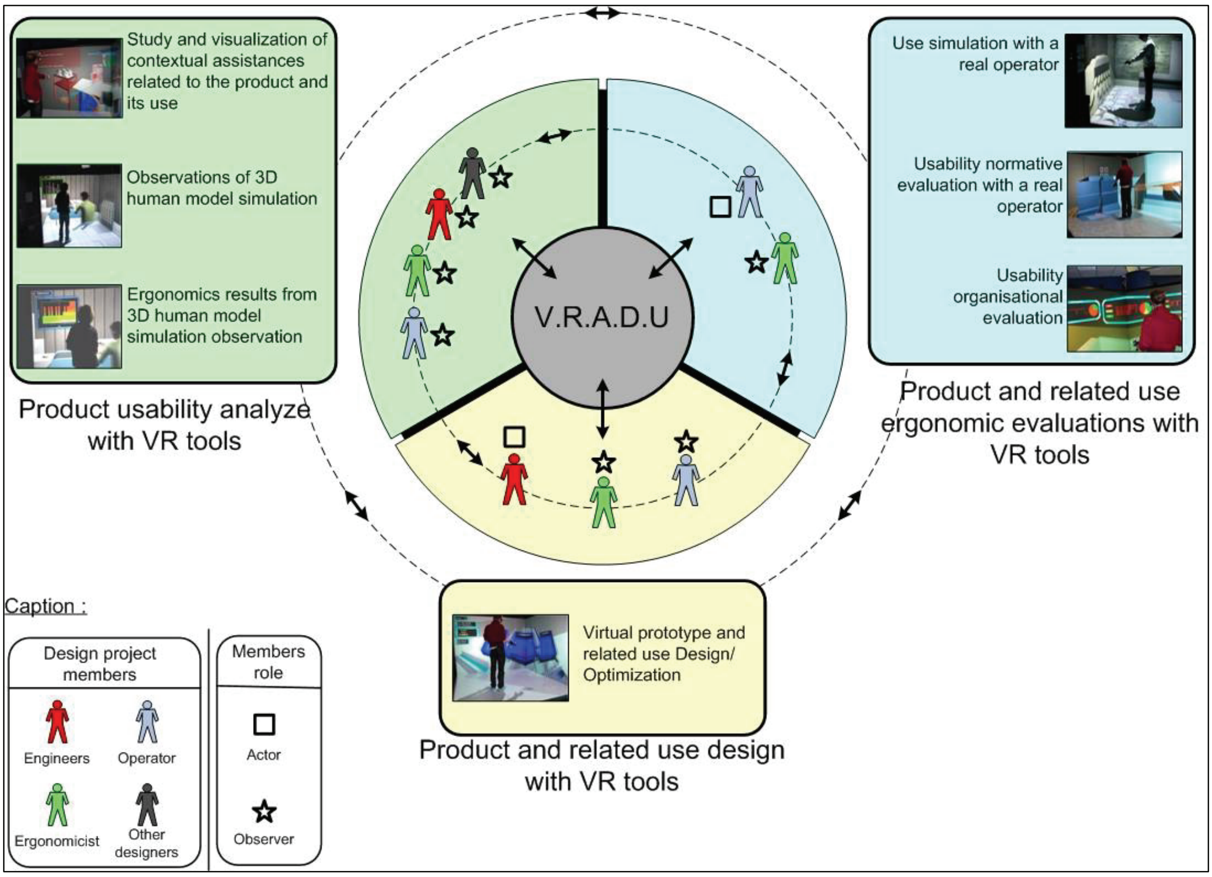


Fig. 8 VRADU methodology

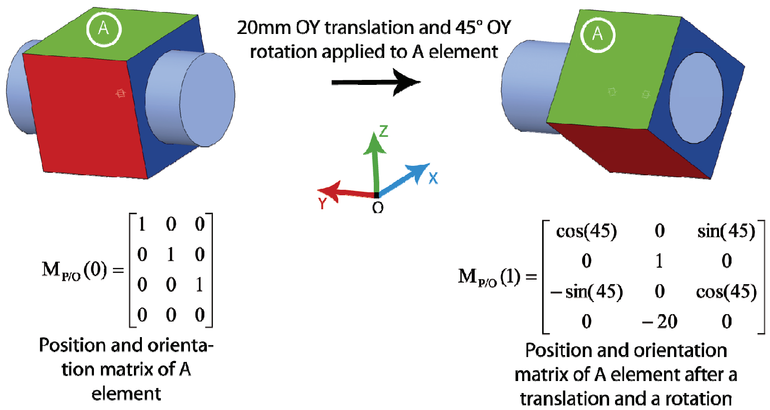
4.3 Product and related use design with VR tools

At this time, engineers have an important role. Indeed, they have to apply modifications to the virtual prototype. Thus, they have a design actor role that allows them to interact with virtual prototype parts. To achieve a direct link with the native CAD model, they use the parametric features of commercial CAD software such as Dassault System's CATIA V5. In fact, when engineers modify the virtual prototype configuration in the VR platform, our self-developed software application also modifies the parameter file connected with the original CAD model (figure 9). Our first results allow the design actor to change position and orientation of the product parts, with direct impact in the native CAD model.

With this method, we achieve a direct link between VR ergonomics simulations and the native CAD model, using a transformation matrix ($M_{P/O}$ matrix) that applies position and orientation as shown in figure 10.

Fig. 9 VP modifications with VR tools

The three first lines of the matrix $M_{P/O}$ represent the rotation applied on a related element. The first line gives the element's rotation around the OX axis, the second around the OY axis, the third around the OZ axis. The last line gives the translation applied to the element. The three terms of this line express respectively the translations in OX, OY and OZ directions.



$$M_{P/O}(0)=\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\\0&0&0\end{bmatrix}\qquad M_{P/O}(1)=\begin{bmatrix}\cos(45)&0&\sin(45)\\0&1&0\\-\sin(45)&0&\cos(45)\\0&-20&0\end{bmatrix}$$

Fig. 10 Transformation matrix used by parameters file

Thus, we achieve a design process for usability, integrating humans in the loop, based on CAD model, 3D human model simulations and VR tools as shown in figure 11.

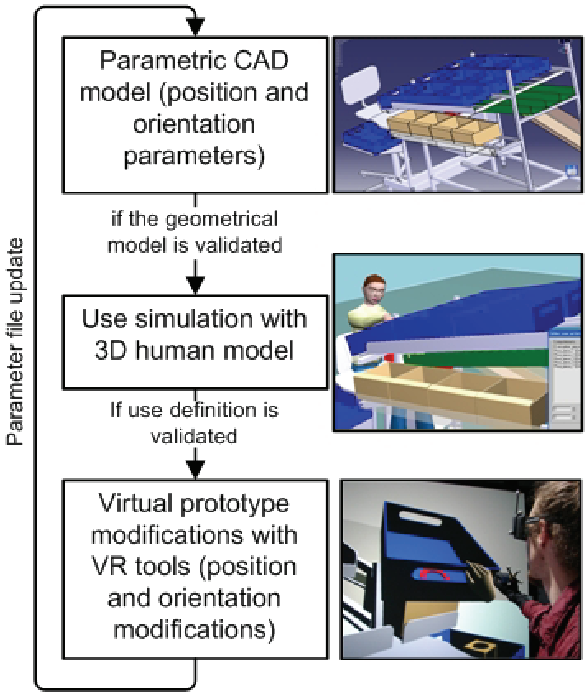


Fig. 11 Usability definition loop based on simulation tools

5 Conclusions

We have presented an original design methodology that integrates human factors simulations with VR tools.

"VRADU" shows good complementarity with 3D human model simulations due to immersion and interaction characteristics made possible by VR tools. It allows designers to analyze 3D human model simulations and ergonomics evaluations. Thus, design team members can easily work together using the virtual prototype which represents the future workplace and its corresponding use.

This ergonomics integration made possible through a design process with VR tools, helps to carry out design for usability with the real operator. It is also possible to achieve ergonomics simulations with a real operator interacting with the future workplace. Thus, the ergonomicist can analyze product usability and give more detailed and understandable modifications.

The modifications on the VP with VR tools are easily made in a more interactive way, compared to classical CAD tools. Engineers can modify the future workplace and at the same time estimate usability improvements. An interactive design process for usability, integrating humans in the loop, is achieved with a direct link with CAD tools.

The next phase of our work will consist in integrating design rules into VR tools. Our objective is to provide design tools to help designers to take into account well known design rules from several disciplines such as material sciences, ergonomics, manufacturing, etc.

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