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ORIGINAL PAPER

Ergonomic analysis in conceptual design stage using a gesture-based modelling tool

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Abstract Commonly, ergonomic analysis of the products' assembly processes starts in the embodiment design phase, when the information of the parts and their interaction are clearly defined. This may imply iterations during the design process for making improvements associated with ergonomic issues. We asked whether it is possible to infer possible ergonomic issues related to the manual assembly process during product conceptualisation. So, we integrated an AR-based modelling tool, in which the user creates and places virtual parts over the context in a top-down design strategy using his/her hands as interface, with an Ergonomic Assessment Module for continuous evaluation of the user postures, movements and forces related to the created parts. In that way, the spectrum of the potential solutions during the conceptualisation phase, when the information about the problem is vague enough, can be delimited and the convergence to the near-optimal solution may be more effective.

Keywords Augmented reality · Conceptual design · Computer aided design · Ergonomics · Upper limb assessment

1 Introduction

In the last years, the human factor is gaining importance in design, engineering planning, manufacturing and maintenance of new products, with the aim of minimise occupational risks in the workspace. Not only on behalf of the workers' health but also in view of the production performance.

Musculoskeletal disorders (MSDs) are one of the more common affections in manual assembly operators, which are believed to be closely related to posture, physical overexertion, duration and frequency of physical effort, discomfort and physical fatigue [1].

Ergonomic design is a vital and complex part of the product design process. However, the designers could encounter several problems in order to find an ergonomically appropriate design solution [2]. Usually, the designers establish ergonomic requirements before starting the conceptualisation but the product is not ergonomically evaluated until a detailed design is obtained. So, ergonomic analysis is laid aside by the designers, whom without tools for decision making, left production engineers and ergonomists in charge to analyse occupational risks in advance stages of the product development process. Thus, the designers need to rely on their own knowledge and experience when making crucial decisions regarding ergonomic issues during product conceptualisation [3].

In this way, product conceptualisation and ergonomic analysis are asynchronous and independent phases within the product design process. This because, at the initial stages, the knowledge about the design problem is limited, making difficult some analysis and decisions. Therefore, ergonomic analyses are commonly carried out during the detail design phase with virtual prototypes or even with with physical ones (see "Traditional Approach" in Fig. 1). In these cases, if product remodelling is needed, the whole cycle is repeated until the resulting model of the product satisfies, among others, the ergonomic criteria.

Currently, there are some commercial tools for ergonomic evaluation that are widely used in the industry. Some of

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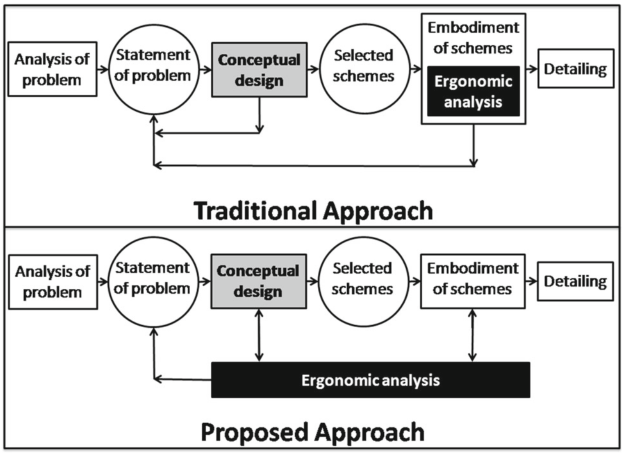

Fig. 1 Traditional design approach vs. Proposed approach with ergonomic analysis

these are stand-alone ergonomic software which are applied independently of the CAD software used during the product design processes (such as SAMMIE, APOLIN, TADAPS) and the other are modules compatibles with commercial CAD software (such as Jack, Delmia, SAFEWORK). In the latter case, designers are able to manipulate both the human form and the product design using an interactive interface. These two kind of tools can provide some assistance during ergonomic design evaluation, but the designer still has to possess substantial experience and knowledge in the field of ergonomics [3]. On the other hand, the simulations provided by these tools are based on non-natural virtual human postures.

Mixed reality (MR) technologies are being used in CAD as an emergent alternative for interactive design. From the authors point of view, interactive design is related to the use of advances and innovative technologies for enhancing the communication and integration of the designer with its virtual prototype (the reader should refer to [4,5] for details in Interactive Design theory). In the present work an Interactive Design process is achieved by employing MR technologies to allow the user to perceive 3D virtual prototypes more clearly and, in most cases, to perform actions in a free and natural way moving his/her hands in a 3D space (3D input). By the use of modelling techniques based on Augmented Reality (AR) environments, the visualisation of the virtual model in a natural scale and in its real position over the real scenario is achieved, so the user's postures related with the product usage can be simulated by the designer during the conceptualisation phase for determining ergonomic risks and designing the product according to these. In addition, a manual gesture-based interaction during the modelling activity implies the user simulates the assembly process while he/she is developing his/her virtual concept model in a natural scale using his/her hands as interface for placing and dimensioning virtual parts [6]. In this way, it is possible to map the virtual space with the real one and infer ergonomic issues related with further phases of the product life cycle. That ergonomic analysis allows increasing the knowledge about the problem, and consequently making the convergence to the design solution more effective and even improving products quality and operators productivity, decreasing occupational risks.

Because of these new trends in modelling tools and the lack of decision tools supporting designers during the conceptualisation stage to converge to a near-optimal solution (in terms of ergonomic aspects) of the design problem, the authors state that it is possible, using gesture-based 3D modelling tools for conceptualisation in AR environments, to analyse ergonomic issues of a product in real-time (see 'Proposed Approach' situation in Fig. 1). This has been addressed integrating an ergonomic analysis module (EAM) to an already developed AR-based 3D modelling tool, air-modelling [6], for monitoring and analysing the users' postures continuously during the design process. Visual information is fed back to the user by using a see-through head mounted display. Thus, ergonomic issues related with the product usage and its manual assembly process can be inferred even from its conceptualisation phase. In other words, ergonomic constraints are added to a highly unconstrained problem such as conceptual design. In doing so, the designer can start to improve his/her design during conceptualisation phase, from the ergonomic point of view, instead of doing only *a posteriori* ergonomic validation in advanced design stages that involve more time and resources if modifications are required.

This work is only based on ergonomics related with anthropometrics and not any cognitive nor experiential processes are taken into account at all to achieve the ergonomic analysis of the products.

This paper is organised as follows: the literature review is presented in Sect. 2, the technical approach is described in Sect. 3, the test and results are presented in Sect. 4. Finally, the discussion and conclusions are summarised in Sect. 5.

2 Literature review

Ergonomic evaluations are commonly carried out in advanced stages of the product development, mainly addressed from two approaches: digital human modelling (DHM) and mixed reality (MR).

2.1 Digital human modelling (DHM) for ergonomic assessment

This approach has been used for ergonomic assessment in different applications such as tool-handle design [3,7], vehicles interface testing [8,9], operation protocols and training programs [10], and assembly processes [11–16], among others. Others authors have proposed their own tools, away from the commercial ones, for ergonomic analysis of manufacturing processes. Sun et al. [17] presented a tool for ergonomic evaluation of work spaces with a case study of a ship operation room. However, programming the human behaviour is not an easy task which could result on non-natural postures and movements. Kaljun and Dolŝak presented an intelligent decision support system for ergonomic design, which is limited for hand tools and its use must be asynchronous with the design stage [3]. Khatib et al. [18] exposed a tool for conceptualisation in which the designer and the ergonomist have a special interface for communication, but the ergonomic assessment is based on 2D manikins and a dedicated ergonomist is required to develop a design. Jung et al. [19] developed an interesting method for DHMs generation but it is not a tool for ergonomic evaluation in itself.

Despite the great utility of DHM in the industry, one of the main issues with this approach is that the movements are obtained through inverse kinematics, giving to the virtual human a robot-like and unnatural behaviour [20].

2.2 Mixed reality (MR) for ergonomic assessment

A new trend for ergonomic evaluation of products is the simulation in virtual reality (VR) and augmented reality (AR) environments. In this evaluation real humans are who execute the movements and experiment the postures related with the usage of the product (e.g. vehicles ergonomics evaluation [21–23]) or with its manufacturing process. Although these simulations are still challenging (according to studies presented by Pontonnier et al. [24] and Hu et al. [1]), they allow a realistic experience avoiding the constructions of physical prototypes to perform ergonomic evaluations.

In manufacturing field, authors like Ma et al. [25], Härtel et al [26] and Whitman et al. [27] presented analysis of weight lifting using VR tools. Dong et al. [28] as well as Bennis et al. [29] analysed assembly operations for maintenance purposes. Qiu et al. [30] as well as Yang et al. [31] presented an applied a case study of the use of MR technologies in ergonomic evaluation of engine assembly operations. Vignais et al. [32] created a tool for assessing and giving feedback, in real-time within an AR environment, for the postures of a user executing assembly tasks. Tian and Duffy [33] presented a tool that allows to achieve dynamic ergonomic assessment with a classification model of job risk. These tools result very useful for analysis of work spaces, however any detected problem implies to go back in the design process, to redesign the manufacturing system or the product itself and to carry out the ergonomic analysis again, iterating up to accomplish the criteria of ergonomics. Jayaram et al. [34] integrated an interactive immersive simulation tool with a commercial ergonomic analysis tool. Afterwards, the same authors presented their own ergonomic analysis tool and compared the results with the commercial one [35].

All these interesting studies are focused on the detailed stage of the design process when the improvements start to imply more costs and efforts in relation with the conceptualisation stage.

2.3 Literature review conclusions and contribution of this paper

From the taxonomy conducted in the literature review, it can be concluded that there are not any tools for supporting decision making process regarding ergonomic issues of a product during its conceptualisation. Existing tools are for ergonomic analysis in advanced stages of the product development and they do not allow a synchronous redesign of the product if any issue is detected. In this way, any modification to the design implies a new iteration in the design process. On the other hand, AR in comparison with VR tools yields a more realistic experience to the user as the virtual model is displayed over a real scene which allows a direct interaction with the context and its spatial restrictions. In addition, for VR tools the construction of the entire virtual workspace is required, which becomes complicated and time-consuming [17]. This is why the proposed approach allows to evaluate in real-time ergonomic issues of a product during its conceptualisation in AR environments using a natural interface to create the virtual model.

3 Technical approach

3.1 AR-Gesture based modelling tool - *air-modelling*

Air-modelling is a tool for solid modelling during product conceptualisation stage in which the user can create, place and dimension virtual parts in a natural scale directly over the real context, with his/her hands, in a top-down design strategy, i.e the virtual model is created by adding new parts assembled in the desired place (see Fig. 2). Air-modelling allows the designer to use the real scene as an information input to verify the dimensions, proportions and positions of the 3D models at the modelling time, visually. This tool is more useful for conceptual design of products whose shape depends mainly on the context, such as furniture, structure frames and pipe networks [6].

As Fig. 3 presents, air-modelling uses a depth camera (Microsoft Kinect®) to calculate the user's joints position vectors, a single-command remote control that the user holds in his/her hand for event confirmation and a USB video camera that captures the context, which includes the fiducial marker that allows the projection of the virtual model over

Fig. 2 Box creation using air-modelling. User view

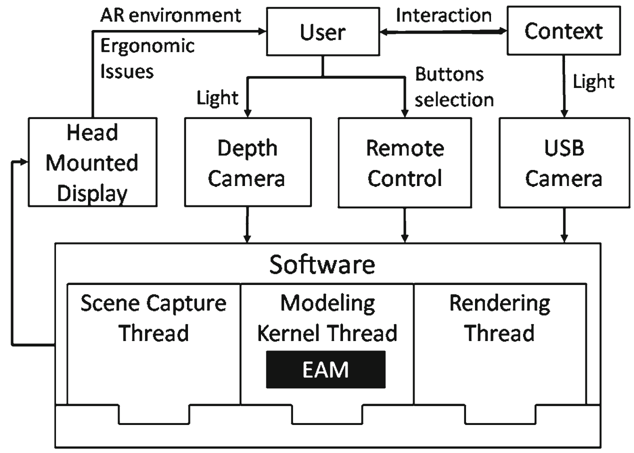

Fig. 4 Integration of the EAM in the air-modelling architecture

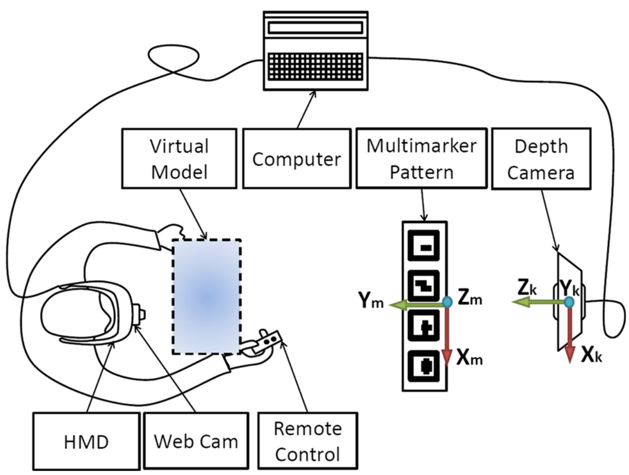

Fig. 3 Air-modelling scene setup

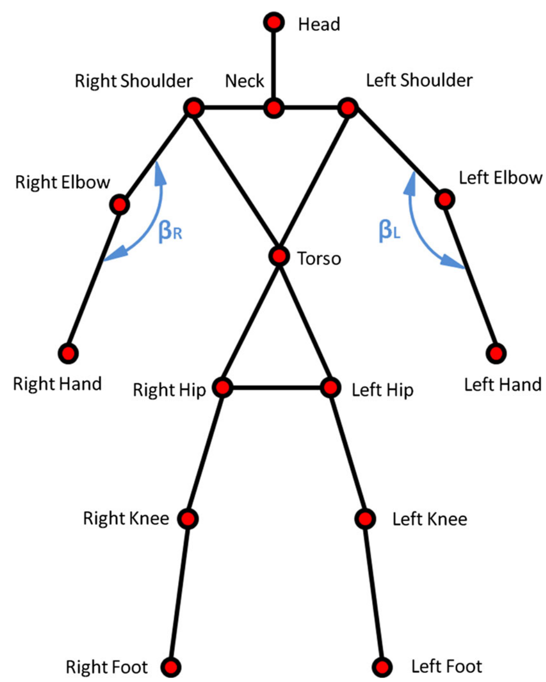

Fig. 5 Skeleton reconstruction using Microsoft Kinect® and NITE™

the context with the correct perspective in the Head-Mounted Display (HMD).

Air-modelling software is composed by three different threads: scene capture, modelling and rendering. The scene capture thread is in charge of capturing the scene, including both the user and the context. In the modelling engine thread, a B-rep (boundary representation) of the virtual models is created, stored and updated according to the user's commands and hands position. The reconstruction of the user skeleton is computed by the library for body tracking NITE™. The AR scene, merging the stream of the real environment captured from the HMD with both the user perspective and the virtual model, is provided by the rendering engine thread. These threads are presented in Fig. 4.

The correct perspective projection is achieved with the ARToolkit library. The virtual model is rendered using OpenGL.

3.2 Ergonomic assessment module—EAM

The inputs to assess the postures of the user during the conceptual design stage are the angles between body parts and the forces exerted by the user. The reconstruction of the user's skeleton with 15 joints provided by the NITE™ algorithm, is employed for calculating the angles between each pair of continuous body parts (e.g. β_R, β_L in Fig. 5). On the other hand, the weight of the virtual parts that the user manipulates are calculated according to the parts' geometry and the density of the pre-selected material. In the modelling kernel thread of the software was implemented the EAM (see Fig. 4) that uses the aforementioned information in order to warn the user in real-time, regarding non-recommendable postures.

The user's postures are evaluated with the Rapid Upper Limb Assessment (RULA) tool [36]. This tool was developed to investigate the exposure of workers to risk factors associated with work-related upper limb disorders. Positions, forces, and frequencies concerns with focus on the upper limbs, neck, and trunk are analysed. RULA associates body postures to numerical values evaluating exposure to risk factors and it uses three scoring tables to compute a final score for each body side. For example, if the upper arm position is in the range of $-20/+20°$, in relation with the trunk orientation, a value of 1 is given, if it is less than $-20°$ a value of 2, if it is in the range of $45/90°$ a value of 3 and if it is more than 90° a value of 4 is associated. With this score and other scores from other limbs, a final score is calculated using three scoring tables provided by the tool (see reference [36] for details). The level of intervention required to reduce the risks of injury due to physical loading on the operator is finally indicated. Postures are classified in acceptable, postures that may be studied, postures that may be changed soon and postures that may be changed immediately. Finally, a coded version of the RULA tool was implemented in the modelling kernel thread of the air-modelling's software.

3.3 Validation of the RULA implementation

In order to validate the implementation of the RULA tool into the air-modelling software, some postures scored using this tool and the module Delmia™ of the Catia™ commercial software were compared. The angles of the test postures were obtained from the air-modelling tool and with this information the postures were replicated in Delmia™, as it is presented in Fig. 6.

Table 1 presents the information of the posture shown in Fig. 6. As it can be noticed, the same RULA scores in both tools were obtained and this validated that the results obtained by the EAM were reliable.

Fig. 6 Results validation against Delmia™

Table 1 RULA results comparison from air-modelling and Delmia™

	Angles	AM RULA score	Delmia RULA score
Right lower arm angle	22, 90°	3	3
Right upper arm angle	51, 17°		
Left lower arm angle	36, 82°	4	4
Left upper arm angle	94, 37°		
Neck side angle	−6, 54°	4	4
Trunk front angle	10, 81°	2	2
Trunk side angle	−9, 54°		
Right total score	N/A	4	4
Left total score	N/A	5	5

4 Results

A tool has been developed for product conceptualisation in AR environments, in which the designer is able to know the evaluation of his/her postures in real-time. The designer can simulate the usage of the product in order to assess the risk that the final user could have. In addition, since air-modelling works with a top-down design strategy, the design process can be associated with the real assembly process and consequently ergonomic risk of the assembly operators can be also analysed. This information allows to consider, during the product concept development, aspects that could imply ergonomic risks in further phases of the product life cycle and to make the required changes in order to improve the ergonomic value of the product.

While the user is developing a product in air-modelling, he/she receives feedback with the evaluation of his/her posture permanently. The user's skeleton reconstruction, highlighting the body parts in risk, is shown through the HMD. Figure 7 presents two different postures evaluated by the EAM. This information appears in the lower left corner of the screen in the HMD (see Figs. 8 and 9) in order to warn the user about ergonomic risks related with the interaction with the product. The colours of the skeleton and the flag given with the final RULA score, warn the designer about the risk level of the posture: green colour means low risk and red colour implies the highest risk. The RULA final score is presented for each side of the body: right side (RS) and left side (LS).

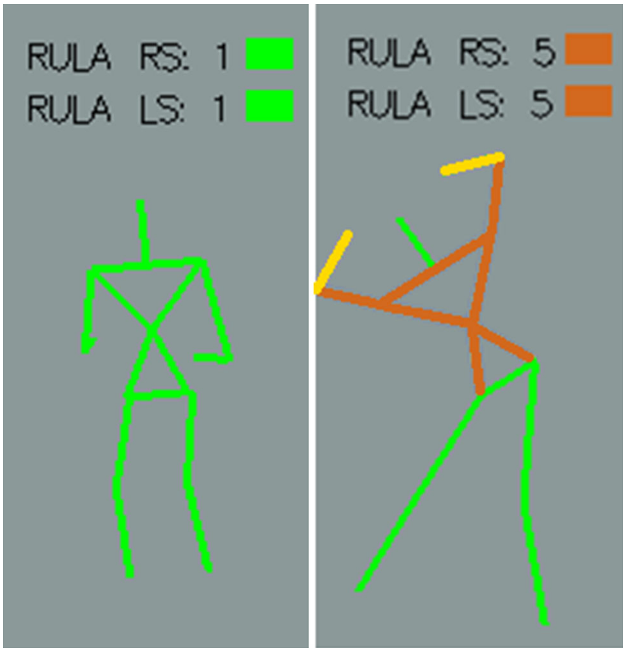

Fig. 7 Posture evaluation presented to the user in air-modelling

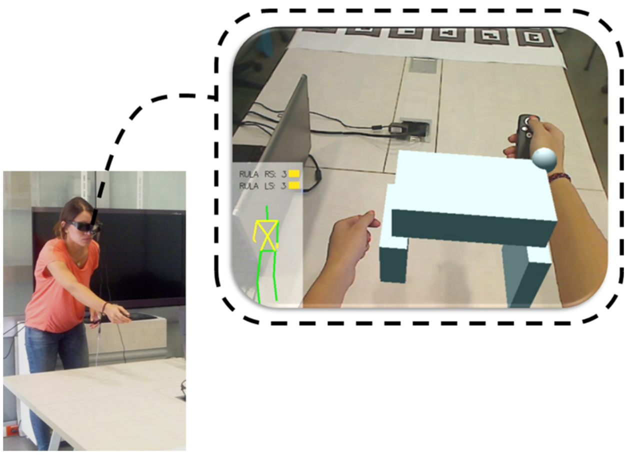

Fig. 8 Posture warned as non-recommendable during the model creation

Finally, we carried out a case study in which a user was asked for conceptualising a bookcase over a certain context, analysing during the modelling the ergonomics issues related with the product usage and its assembly process. Figure 8 presents a moment in which the user is releasing a virtual board. The EAM is warning the postures of both the right arm and the trunk considering the weight of the virtual part that is being manipulated. That means that possibly the assembly operator could execute a similar posture during the product installation in that context. Although the posture needs to be analysed, it does not represent any considerable risk yet.

On the other hand, Figure 9 presents a screen capture in the moment in which the user was simulating the usage of the

Fig. 9 Posture warned as non-recommendable while the product usage was being simulated

bookcase. Specifically, she was trying to reach something in the upper level of the bookcase. It is noticed that in the ergonomic evaluation, the neck is highlighted as a body part in notable risk. This means that possibly the final user of the product could have the same ergonomic implication while using the bookcase.

Therefore, the designer should analyse postures taking into account, among others, the spatial restrictions that the context imposes to the product configuration, usage and assembly.

In addition, when the user creates and/or locates a new part with a non-recommendable posture, a new instance is added to the final ergonomic report. At the end of the design session the user can review the report with the list of risky parts and their RULA scores and skeleton posture at the interaction moment. With this information the designer can determine the required improvements to be implemented in order to minimise occupational risks in the future interaction with the product.

5 Discussion and conclusions

Modelling in natural scale in augmented reality environments using the hands as interface, allows the designer or user to analyse, in real-time, ergonomics aspects related to the interaction with the product during its conceptualisation. The designer can simulates the postures involved in the product usage and assembly, in order to analyse ergonomic risks to which the user or the assembly operators could be exposed and to perform necessary changes in the product or process for improving its ergonomic value. In this way, adding ergonomic constraints and evaluation during the conceptualisation stage, when the information about the problem is vague enough, keeps a spectrum of potential solutions to the design problem within reach. In this way, the convergence to the near-optimal solution may be more effective possibly avoiding some iterations in the design process.

One of the main advantages of the AR technology is that the scene does not have to be modelled. On the contrary, the real scenario is used as an information input. In this way the user is able to perceive in a realistic way and take into account, during the conceptualisation process, the spatial restrictions that the scene imposes to the product shape, configuration, usage and assembly process. However, it is clear that the AR-based modelling is not helpful for all products, as in the case of too large-scale products such as air planes, ships or buildings or too small-scale product such as watches or cellphones. This becomes more relevant for products whose shape, configuration and dimensions depend mainly on the environment, such as furniture, piping networks and structural frames.

A limitation of the proposed tool is the fact that the ergonomic analysis is based on the anthropometrics of the designer. Thus, it is possible that the final user or the assembly operator belongs to a different percentile and, in this way, his/her posture against the product usage or assembly could be different. As future work it would be interesting to infer and analyse the postures of users belonging to percentiles different to the one of the designer.

The shape and configuration of a product can change between its conceptualisation and the detailed design stage. So, traditional ergonomic analysis in advanced stages of the product development is still required. In this way, the proposal is not to translate the ergonomic analysis phase (commonly carried out in the embodiment of schemes stages, see Fig. 1) to the conceptual design stage, but to start analysing and improving ergonomic issues related to the general shape of the product from the conceptualisation design stage, when the changes in the design do not imply representative costs yet.

RULA tool was developed without the need for specific equipment [36]. With this tool the ergonomic evaluation can be carried out by observation using only a clipboard and a pen. So, this method does not demand for high precision in the calculation of the angles between the body parts. In this sense, the lack of high precision in the skeleton reconstruction provided by Kinect®) and NITE™ library is not very influential. Moreover, RULA is created for detecting in first instance ergonomic risk and a deeper and exhaustive analysis is recommended if the related product or the worker routine is not susceptible to change.

It would be interesting to analyse the effects of adding realistic physical interaction between parts, with a dynamic engine. This would be closer to the way in which the designer develops his/her model with the real assembly process of the product. In addition, the feedback of forces related with parts lifting, possibly influences the designer's postures and movements while is developing a 3D model using air-modelling. In this way, dynamic ergonomic analysis could be carried out in order to analyse in detail the manual assembly work of the product and even its usage.

Finally, applying ergonomic constrains in real-time to the conceptualisation stage facilitates the convergence to the design solution, possibly avoiding some iterations in the design process. In addition, the conceptualisation stage could be explored and used as an information source for further phases of product development.

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