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Digital Manufacturing and Virtual Reality for Tractors' Human-Centred Design

Fabio GRANDI[a], Margherita PERUZZINI[a,1], Luca ZANNI[a], Claudia Elisabetta CAMPANELLA[b] and Marcello PELLICCIARI[a]
[a] *University of Modena and Reggio Emilia, Dept. Engineering "Enzo Ferrari"*
[b] *CHN Industrial Spa*

Abstract. Human-centred design is based on the satisfaction of the user needs related to performances, aesthetics, reliability, usability, accessibility and visibility issues, costs, and many other aspects. The combination of all these aspects has been called as "perceived quality", that is definitely a transdisciplinary topic. However, the "real" perceived quality is usually faithfully assessed only at the end of the design process, while it is very difficult to predict on 3D CAD model. In this context, digital manufacturing tools and virtual simulation technologies can be validly used according to a transdisciplinary approach to create interactive digital mock-ups where the human-system interaction can be simulated and the perceived quality assessed in advance. The paper proposes a mixed reality (MR) set-up where systems and humans interacting with them are digitalized and monitored to easily evaluate the human-machine interaction. It is useful to predict the design criticalities and to improve the global system design. An industrial case study has been developed in collaboration with CNH Industrial to demonstrate how the proposed set-up can be validly used to support human-centred design.

Keywords. Human-centred design, digital manufacturing, virtual simulation, human-machine interaction

Introduction

Human-centred design (HCD) focuses on the inclusion of human factors in product and system design in order to respond to physical, psychological, social and cultural needs of human beings [1]. Human factors specifically refers to research "regarding human psychological, social, physical, and biological characteristics, and working to apply that information with respect to the design, operation, or use of products or systems for optimizing human performance, health, safety, and/or habitability" [2]. As a consequence, HCD consists of the application of human-related information to the design of tools, machines, systems, tasks, jobs, and environments for safe, comfortable, and effective human use. As far as industrial system design, the optimization of posture, physical overload, perceived effort, discomfort, and physical fatigue is fundamental to satisfy the users' needs and prevent musculoskeletal disorders [3]. In this context, the analysis of human factors has a central role in the understanding of human behaviours and performance interacting with socio-technical systems [4], and the application of that understanding to design of interactions [5], in a transdisciplinary way.

[1] Corresponding Author, Mail: margherita.peruzzini@unimore.it.

In the last few years, the assessment of the perceived quality gained a growing attention within companies, which are increasingly focusing not only on the way their products work, but also on how the users interact with them and how users feel during the use. However, the investigation of the perceived quality is not a trivial task since it includes a multitude of factors that are reciprocal connected and influences each other. Designers and engineers have to consider both physical and psychological comfort perceived by the product users, as well as usability and the overall human-product interaction in order to design a successful product [6].

Traditionally the analysis of human-related aspects of a product is based on physical prototypes, which creation increases development times and cost. Thus, there is a strong need for integrating human factors in the design and verification of industrial processes using advanced simulation techniques [7]. Nowadays, with the constantly increase of the computational power and the decrease of equipment size, there is a lot of simulation tools to be used for virtualizing the product and assessing the human-product interaction in advance, and a variety of devices that allow the monitoring of the human physiological parameters available at a reasonable price. Also wearable instruments designed for hands-free operation can be used during the design stages within immersive environments in order to reduce the intrusiveness and allow the wearer to stay focused on their main task and be assisted by the wearable rather than be distracted, recording continuously biometric data without additional effort [8].
The aim of this paper is to present an example of transdisciplinary engineering based on the use of digital manufacturing tools and virtual reality technologies for tractors' design by the adoption of interactive environments and preventive analysis of human factors. The paper provides an overview of the scientific and industrial state of art on the most common methodologies for human-product interaction into virtual environments and monitoring tools to be adopted for human monitoring, defines an experimental MR set-up for human-monitoring on virtual prototypes during design stages, and applies this set-up to an industrial case study focused on tractors' design.

1. Research background

Digital emerging technologies can support simulation-based engineering for preventive analysis before the products or systems are physically realized. Such tools allow products and interaction tasks to be simulated on digital mock-ups, and human actions and behaviours to be reproduced by digital human models (DHMs) [9]. Examples of virtual simulation DHM tools used are: Siemens JACK, Dassault Systèmes CATIA/DELMIA HUMAN, RAMSIS, SANTOS, Pro/ENGINEER Manikin Analysis, SAMMIE, 3DSSPP, Anybody® Modeling System. Using these tools, the biomechanical attributes of specific postures, the visual scope and the reach envelope of users representing specific populations can be analysed [10]. Some tools also include ergonomic observational methods NIOSH equation, Rapid Upper Limb Analysis (RULA), Ovako Working posture Analysis System (OWAS) and provide a quick, virtual representation of human beings in a simulated working environment to identify the ergonomic problems. Furthermore, Virtual Reality (VR) technologies are used to create a 3D immersive simulation where users are immersed and user experience can be validly simulated and assessed. Numerous examples are available in literature. Honglun et al. (2007) [11] used a virtual human model to reproduce the real human characteristics in virtual environments for product ergonomics analysis and demonstrated that digital simulations allow to detect design problems in advance, with the reduction of time and cost in prototype making. Also Aromaa and Väänänen (2016) [12] proved the importance of using virtual prototypes in human-centred design supported by VR environment to assess visibility, climbing, postures, space, reach and use of tools. Abidi et al. (2013) [13] performed ergonomics analyses of a sport utility vehicle in a semi-immersive virtual environment, which help to make the users aware about their own feeling inside the real car. Peruzzini et al. [14] also proposes virtual environment to support workstation design by virtual and mixed prototypes.

Experimental implementations often consisted of multiple devices that contribute to the goal of valid and reliable evaluation of drivers' state, and, to some extent, are capable of estimating up to four driver state constructs like cognitive distraction, mental workload, mental fatigue, and emotions [15]. The interest in understanding how users perceive the final product is nowadays crucial for the product success and integrated model for user experience investigation has been recently proposed [16].

Traditionally, human factors analysis is mainly based on the subjective assessments involving real users by questionnaires or interviews. However, such techniques could not provide objective results and are hardly executed in real-time. More structured subjective assessments have been developed. Among them, NASA-TLX is the most widely used to evaluate the mental workload. It consists in six evaluators, which are Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration Level and is divided in two steps, ratings and weights. It collects raw data from the subject and calculates the weighted workload score, which is output to a text file [17]. Zheng et al. (2011) [18] also adopted NASA-TLX for human factors assessment during the design phase.

Unfortunately subjective data, when used alone, do not provide sufficient information to evaluate the human stress and the mental effort during task execution [19]. To overcome such limitations, in the last years the monitoring of physiological parameters is entering also in the design area. However, the main issue is to find a robust correlation between the monitored physiological parameters, the user experience, and the perceived quality. Main examples of data collection during on-filed testing refer to heart rate (HR) and heart rate variability (HRV), electro-encephalogram (EEG) and electro-dermal activity (EDA) also monitored by the galvanic skin response (GSR). About physiological measures like heart rate or respiration, there are relatively simple and low cost instrumentation that allow recording of vital parameters and track the human activity. About physiological parameters monitoring, various researches showed the correlation between vital signs and mental workload. It is not new that HR and HRV can be used as the simplest indicators of users' workload; in particular the increase of the HR and the decrease in the HRV can indicate an increase in the mental effort [20]. Also respiration measurement (i.e., rate and volume of respiration) was used to assess the levels of human stress, generally in conjunction with other physiological measures. However, the main drawback of respiration monitoring systems is the intrusiveness since they require users to wear a belt around their chest.

Regarding pupillometry and electrooculography, eye-tracker technologies are widely diffused for users' monitoring, thanks to more ergonomic-shape glasses and non-contacting camera that observes the eyeball plus image processing techniques. A lot of studies have recently focused on its application for human workload analysis and the correlation between eye-based signals and human factors. Martin et al. (2011) [21] applied eye tracking to analyse mental workload characteristics in air traffic controllers' activity. Similarly, Sharma and Gedeon (2012) [22] found out that eye gaze and pupil dilatation provide useful information on the individual's attention source and stress. Also Marquart et al. (2015) [23] found that the human workload increases with the increase of the blink latency and, on the contrary, decreases with the increase of blink duration and gaze variability. Results confirmed that eye-tracking technique is a powerful approach to study mental workload during a complex activity.

2. The experimental set-up

2.1. The simulation approach

The study is based on task analysis, digital simulation and virtualization by using VR technologies in order to create an interactive mixed reality (MR) set-up to support human-centred design of industrial products. Task analysis allows focusing on the activities to be simulated by subdividing them into a set of sub-tasks, identifying the simulation fixed and variable parameters and external conditions, and highlighting the human-system interactions. Digital simulation allows creating a digital environment where human-product interaction can be simulated in advance and predictive analysis can be carried out during design stages. Initially, digital simulation is executed in a desktop-based modality within the JACK toolkit, which allows digitalizing the product layout and the human operations by virtual manikins. It allows easily replicating the sequence of actions and predicting the user movements. Finally, virtualization is based on the link between the digital model and the VR environment where users can directly interact with a MR prototype and real users' actions are tracked by motion capture technologies and monitored by human physiological data sensors.

The proposed approach allows to analyse the user experience based the study of the interaction between the human beings and the virtual product or system, digitalized and simulated by the MR prototype. Interaction is studied by collecting data about behavioural and cognitive responses thought a set of metrics, properly selected for the specific case study. Metrics aims at measuring both physical and cognitive workload in terms of postural comfort, physical stress and fatigue on one hand, and visibility and accessibility, simplicity of actions, interaction support and satisfaction on the other hand. Such model is based on the Norman's model of interaction [24]. The experimental set-up

In the present research, different software tools compose the set-up architecture, as follows:

- Siemens JACK for product digitalization;
- VICON tracking system for real users' tracking and manikin digitalization;
- HAPTION RTI plug-in for connection among real user movements and virtual manikin movements.

From the hardware viewpoint, the set-up includes:

- a set of eight VICON Bonita cameras for optic tracking;
- a set of 3D printed rigid bodies with markers for full body marking;
- a GoPro camera to record the scene;
- a pair of Tobii Pro Glasses 2 to capture eye movements;
- a Bio Zephyr BioHarness sensor to record human physiological data;
- a XSENSOR carpet to record seat pressure maps.

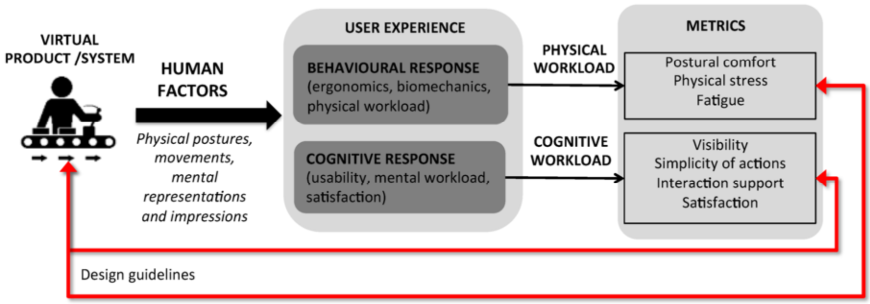

Figure 1. The simulation approach.

The MR mock-up has been realized by using some physical parts from the real tractor, which were assembled to recreate the tractor cabin in the simulation environment. Only parts with determinant physical interaction have been considered (i.e., seat, steering wheel, operating levers, main command buttons). Three different units have composed the final prototype of the tractor cabin: the right trim, the seat, and the steering wheel. All the units are movable and the driver has the possibility to adjust them according to his preferences. This is quite useful to deepen the more confortable conditions during experimental testing.

Table 1 shows, for each tool used in the MR envionrment, the monitored parameters and the collected data. It provides an overview of how the users are monitored and the perceived quality analysed in the study. Figure 2 shows the experimental set-up.

Table 1. Tools for human-machine interaction analysis.

Selected tool	Tool typology	Monitored parameters	Collected data
Siemens JACK	Occupant packaging toolkit	Dreyfuss 3D index	Human joint angles
CANanalyzer	Signal monitoring	CAN data	Command sequence and frequency of use
Tobii Glasses 2	Eye Tracker	Eye tracking (ET) (eye fixations)	Gaze plot, Heat maps
Zephyr BioHarness 3.0	Multi-parametric wearable sensor	Heart Rate (HR)	HR diagram
		Breathing Rate (BR)	BR diagram
		Body activity (VMU)	Activity diagram
		Posture	Stooping on sagittal plane
XSensor IX500	Pressure imaging	Seat pressure	Pressure maps
GoPro Hero 3	Camera	-	Videos of users and the surrounding environment

3. The industrial case study

3.1. Case study description

The case study has been developed in collaboration with CNH Industrial, a global manufacturer of agriculture and industrial vehicles, with more than 64 manufacturing plants and 50 research and development centres in 180 countries. Its production is divided in 12 brands, from tractors to trucks and buses, as well as powertrain solutions for on-road and off-road and marine vehicles. The case study focused on the analysis of user experience on tractors, with the final aim to support human-centred design. The study is based on the virtualization of the cabin, where the tractor driver works and interacts with commands and controls, and the monitoring of the driver's physical and mental workload to understand the level of comfort, the usability of the interfaces, the level of stress, and the perceived quality.

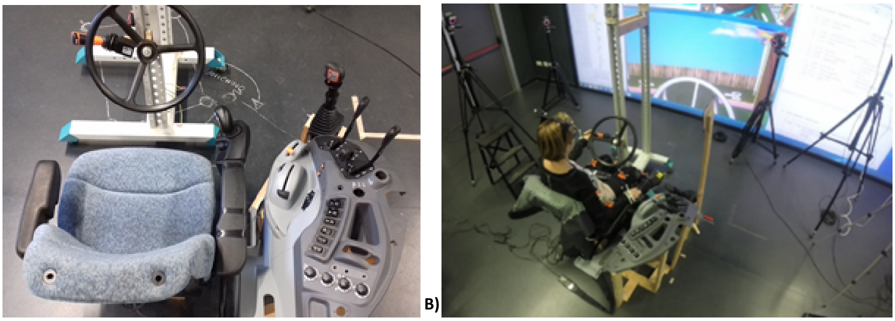

Figure 2. The MR simulation set-up: MR mock-up (A) and integrated VR environment by motion capture

The case study focused on the simulation of the cabin of APL 16 x 16 tractors, which is one of the best-selling products. The scope was to assesse the product quality perceived by users in order to improve the cabin design on the basis of human performance and users' feedback. First of all, task analysis was carried out by observing an expert professional driver executing different missions on the real product during field tests. Purpose of task analysis was to highlight the most relevant missions and tasks, in order to collect data and evaluate the critical issues. The specific case study focuses on the plowing task, which is one of the most frequent in agriculture. CAN data, GoPro videos and eye tracker data were recorded during real human-product interaction; it allows defining how the cabin commands are used and highlighting the main features of the human-system interactions. Focusing on the time-series graphs obtained by data post-processing, it was possible to detect the most relevant sub-task and their sequence. After that, significant 3-minute sequences of task execution were replicated in the MR environment. The main sub-tasks of the plowing task were: 1) initial setting phase, 2) plowing (al least for two minutes), 3) end-of-field manoeuvres, and 4) tractor reset. The 3-minutes sequence was translated in a numbered list, in which every operation is identified by a code, a time and a possible command to activate. Table 2 described the sub-tasks analysed, focusing on the user activities and the used commands.

Table 2. Selected plowing task

Sub-task	**Activities**	**Commands used**
Initial setting phase	Set plow height and sensitivity	Shuttle, EDC Work, Diff lock, Potentiometers, 4WD
Plowing	Furrow depth control, direction control	Potentiometers, EDC Draft Position
End field manoeuvres	Change of directions, change of plow height	Shuttle, EDC Work, EDC Raise
Tractor's reset	Setting road setup	Shuttle, EDC Raise, 4WD, Diff lock

3.2. Digitalization and simulation

The digital simulation was firstly executed in a desktop-based modality within the JACK software toolkit, which allows digitalizing the product layout and the human operations by virtual manikins. With the help of video-recorded data from the real operations monitored during field tests, the selected sequence is divided into a set of postures, and each posture is re-created manually on the software. This kind of simulation represents the first step to digitize human-machine interaction and to carry out human-centred design in numerous companies. However, this approach requires a great effort to create realistic simulation: many hours have to be spent to replicate real users actions with manikins and the final result strongly depends on the subjective impressions of the expert that recreates the scene. Furthermore, the desktop-based simulation focuses on postures, and does not allow investigating the complete sequence of task between different postures.

To overcome such limitations, the simulation is carried out in a MR environment, where tasks are replicated by real users in a virtual environment and tracked by motion capture system. Four users where involved in experimental testing, acting as tractor operator and executing the plowing task as described during the task analysis. Users were equipped by wearing the eye tracking system (Tobii Glasses 2) and the biosensor (Zephyr BioHarness 3.0). The sensorized carpet (XSensor) recording data about eat pressures where fixed to the seat during the simulation. Within the virtual environment, users and physical objects were tracked by the optical tracking systems (VICON infrared cameras) to create their "digital twin" to put into the virtual scene for further process simulations. An external camera (GoPro) recorded their actions. Finally, the tracked users movements were imported into the virtual environment on virtual manikins to obtain a virtual sequence of actions, to be analysed by digital tools. Two experts were involved in camera configuration, data acquisition and post-processing.

Metrics collected during experimental testing includes physical, physiological and cognitive measures, as described in Table 3. Physical metrics collected during the simulation are a list of 28 comfort ratings, provided by Dreyfuss 3D Data Source included in JACK toolkit, in which every value represents a particular body angle. The biosensor collected most relevant physiological data of users, such as heart rate, breath rate and posture parameters. The eye tracker provided to record user point of view.

Table 3. Evaluation metrics collected during the study

Monitored parameters	**Description**
Dreyfuss 3D	Human joint angles, Comfort ratings (28)
Eye fixation	Gaze plot, Heat maps
Heart Rate (HR)	Heart beats per minute
Breathing Rate (BR)	Breath per minute
Activity (VMU)	Magnitude of resultant vector of mean acceleration in 3 directions
Posture	Stooping angle on sagittal plane
Seat pressure	Pressure maps of seat

3.3. Experimental results

Data collected from the external camera and the digital environment were synchronized in order to link the obtained data for a specific human action. Each sequence of actions corresponding to a specific sub-task was divided into a set of posture, in order to discretize the analysis. As a result, for each posture a set of 26 human joint angles were collected and evaluated by Dreyfuss 3D method. Figure 3 shows an example of data synchronization between the MR environment (on the right) and the virtual environment (on the left) and results about the user physical stress by Dreyfuss 3D evaluation, executed in real time. Dreyfuss 3D results investigate the users' physical stress. Measured values are compared with a pre-defined comfort range: it they exceed, a yellow bar in the chart expresses the corresponding discomfort. Results obtained on all postures involved in the plowing task (average values among all users) are shown in Figure 4. Also physiological data collected by the biosensor were processed and summarized in time domain graphs as shown in Figure 5. Thanks to the timeline, they were reported to the postures assumed and executed actions during the task in order to find significant correlations. The correlation between physical stress data and physiological data allows highlighting also mental stress condition in order to better understand human-machine interaction. In the case study, it was used to investigate how the interface commands were used during task execution and to study the frequency and sequence of actions, with the final aim to support product design review and comparing the human performance on different layouts.

Figure 3. Results about physical stress by Dreyfuss 3D data for a specific posture

Peso	Dreyfuss 3D Analysis	COMPILA Low	High	Pos sec Mode	1	2	3	4	5	6	7	8	9	10	11	12
					2	3	9	15	19	24	28	32	44	46	51	56
0,5	Head Flexion	-30	30	0	45,2	45,2	8,3	10,0	42,8	45,2	45,2	45,2	45,2	45,2	45,2	45,2
1	Head Lateral	-20	20	0	-12,9	-20,0	-20,0	-20,0	-1,5	-20,0	20,0	20,0	5,2	3,2	20,0	-8,9
1	Head Rotation	-45	45	0	-0,1	13,1	-43,6	-45,4	-12,1	10,6	2,0	-2,2	1,1	-20,1	-5,6	-7,6
1	Upper Arm Flexion Right	-15	35	10	28,8	22,9	112,7	112,8	110,5	26,7	28,3	26,8	27,2	####	12,4	59,7
1	Upper Arm Flexion Left	-15	35	10	7,4	7,2	48,5	49,9	47,4	11,4	7,0	9,0	37,1	39,8	51,4	35,9
1	Upper Arm Elevation Right	0	30	15	26,1	10,2	109,6	112,3	94,9	13,1	58,6	58,7	11,1	101,9	19,3	67,8
1	Upper Arm Elevation Left	0	30	15	14,3	15,4	28,2	27,5	16,8	13,3	12,8	12,3	27,0	24,1	4,9	19,4
1	Humeral Rotation Right	-60	40	-10	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6
1	Humeral Rotation Left	-60	40	-10	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6
1	Elbow Included Right	80	165	123	154,9	129,4	90,1	91,8	85,4	108,9	109,9	113,4	144,6	77,2	128,9	114,1
1	Elbow Included Left	80	165	123	124,9	137,8	137,0	132,5	141,3	145,1	140,8	144,1	142,4	148,1	149,0	143,0
1	Forearm Twist Right	0	98	49	3,0	3,0	42,7	103,0	124,0	46,5	3,0	3,0	3,0	3,0	3,0	6,4
1	Forearm Twist Left	0	98	49	64,6	61,1	17,1	16,6	4,5	52,5	57,6	57,1	12,5	11,5	3,0	6,6
0,2	Wrist Ulnar Deviation Right	0	10	5	-9,1	13,4	33,3	-33,0	-45,0	12,0	37,7	43,9	-45,0	38,4	-13,7	45,0
0,2	Wrist Ulnar Deviation Left	0	10	5	31,5	21,7	13,4	11,8	10,2	18,8	33,0	32,9	19,1	16,0	19,8	18,8
0,1	Wrist Flexion Right	-25	45	10	20,3	27,0	-85,0	-60,0	-62,4	-30,6	13,8	7,7	54,5	5,4	53,8	-85,0
0,1	Wrist Flexion Left	-25	45	10	6,5	-21,7	7,1	10,0	9,4	30,7	24,3	24,2	16,5	10,0	17,6	17,3
2	Torso Recline	10	30	20	21,5	29,9	28,8	26,3	27,8	32,7	33,5	34,8	34,1	35,2	23,0	32,4
1	Trunk Thigh Right	95	120	108	122,2	129,7	112,8	109,1	116,2	130,1	129,7	132,5	126,9	130,7	116,6	126,6
1	Trunk Thigh Left	95	120	108	127,1	135,6	137,1	131,1	137,2	136,8	141,9	142,6	154,1	157,6	125,7	154,0
1	Leg Splay Right	-5	20	7,5	11,0	10,2	-6,5	-3,9	-4,4	11,1	6,7	7,1	-8,3	-8,5	0,2	-8,0
1	Leg Splay Left	-5	20	7,5	16,3	15,9	30,0	30,0	30,0	14,3	17,7	17,1	30,0	30,0	24,9	30,0
1	Thigh Rotation Right	-15	15	0	-10,4	-6,1	5,9	2,5	0,8	-2,2	-0,2	-2,1	9,6	8,4	-3,9	5,5
1	Thigh Rotation Left	-15	15	0	-23,4	-26,3	-45,3	-42,0	-40,9	-21,5	-31,6	-28,1	-50,0	-49,1	-18,7	-50,0
1	Knee Included Right	95	135	115	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1	Knee Included Left	95	135	115	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0,2	Foot Calf Included Right	85	110	97,5	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0
0,2	Foot Calf Included Left	85	110	97,5	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0

Dreyfuss 3D Analysis	16	13	15	14	16	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
	63	68	72	78	87	98	100	103	108	120	121	129	133	137	145	157	166	167	181	186	187	189	192	195	199
Head Flexion	45,2	15,4	19,8	4,5	45,2	15,4	4,5	19,8	45,2	45,2	45,2	0,5	15,6	7,5	45,2	45,2	45,2	45,2	45,2	45,2	45,2	45,2	45,2	12,1	45,2
Head Lateral	-20,0	-20,0	-20,0	-20,0	-20,0	-20,0	-20,0	-20,0	-20,0	-20,0	-15,4	-20,0	-20,0	-20,0	-20,0	-20,0	-20,0	-20,0	-16,6	-20,0	5,9	20,0	-17,7	-20,0	-20,0
Head Rotation	8,8	-49,8	-48,9	-52,1	8,8	-49,8	-52,1	-48,9	8,8	15,7	-0,6	-41,6	-48,1	-30,9	-15,9	11,2	-1,5	19,3	0,1	9,2	-4,5	-6,9	3,4	-40,2	0,7
Upper Arm Flexion Right	13,1	31,9	####	85,4	13,1	31,9	85,4	####	13,1	39,8	3,9	113,6	112,1	113,1	42,8	48,2	15,8	19,0	9,5	12,2	3,7	10,8	74,6	####	44,3
Upper Arm Flexion Left	9,6	-4,8	-5,7	-10,9	9,6	-4,8	-10,9	-5,7	9,6	3,7	4,1	-20,2	12,2	-17,6	-21,9	13,3	37,4	-15,3	3,9	3,4	5,9	12,9	-18,0	-15,6	22,0
Upper Arm Elevation Right	-23,8	-1,8	100,7	-39,9	-23,8	-1,8	-39,9	100,7	-23,8	-10,6	26,9	124,3	106,5	115,4	26,8	-9,7	16,8	21,5	26,9	8,4	67,3	76,6	52,8	112,9	-2,2
Upper Arm Elevation Left	32,7	31,0	29,7	31,4	32,7	31,0	31,4	29,7	32,7	11,2	14,1	21,3	3,8	13,5	22,0	10,0	28,8	19,0	7,8	18,0	17,5	16,1	27,9	13,8	6,5
Humeral Rotation Right	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6	-24,6
Humeral Rotation Left	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6	-29,6
Elbow Included Right	137,1	154,1	48,1	177,6	137,1	154,1	177,6	48,1	137,1	155,0	120,2	116,1	105,0	86,4	125,9	162,9	118,7	109,7	126,2	126,0	105,2	106,8	166,5	38,0	164,1
Elbow Included Left	137,8	137,7	137,1	137,7	137,8	137,7	137,7	137,1	137,8	141,4	130,9	133,2	130,2	122,8	133,0	142,5	145,0	103,3	143,1	144,0	129,8	135,3	94,2	128,2	148,8
Forearm Twist Right	3,0	3,0	5,0	3,0	3,0	3,0	3,0	5,0	3,0	3,0	3,0	50,6	74,6	116,7	3,0	3,0	3,0	3,0	3,0	3,0	3,0	13,9	3,0	66,8	3,0
Forearm Twist Left	61,5	72,6	73,2	79,8	61,5	72,6	79,8	73,2	61,5	58,8	57,4	90,9	18,2	83,7	82,0	45,2	17,5	70,2	64,5	56,0	51,6	50,5	82,1	84,5	50,6
Wrist Ulnar Deviation Right	-40,8	-9,1	45,0	-40,1	-40,8	-9,1	-40,1	45,0	-40,8	6,0	26,1	31,2	5,3	-45,0	45,0	-9,6	-17,8	9,2	27,9	12,2	45,0	-45,0	-10,1	45,0	-19,0
Wrist Ulnar Deviation Left	34,0	24,3	29,0	38,1	34,0	24,3	38,1	29,0	34,0	26,8	42,0	21,5	17,2	4,7	10,1	14,5	19,4	29,6	40,1	27,4	30,1	33,3	45,0	1,2	28,1
Wrist Flexion Right	55,2	67,9	-10,6	25,8	55,2	67,9	25,8	-10,6	55,2	31,7	64,0	-85,0	-85,0	-50,1	56,1	22,1	41,6	43,6	4,9	42,9	-48,0	-85,0	47,8	-85,0	33,1
Wrist Flexion Left	-0,1	34,2	32,1	17,0	-0,1	34,2	17,0	32,1	-0,1	-10,0	16,0	-27,1	12,9	14,4	-3,6	10,1	33,9	5,2	17,7	-37,1	6,4	8,1	17,7	19,5	19,2
Torso Recline	32,4	36,1	32,8	35,9	32,4	36,1	35,9	32,8	32,4	31,9	30,8	32,1	32,4	34,4	37,4	33,1	31,9	26,4	38,2	35,1	35,7	37,0	-10,9	37,1	33,9
Trunk Thigh Right	114,2	113,7	111,8	116,0	114,2	113,7	116,0	111,8	114,2	122,9	125,9	111,9	120,2	117,0	131,1	125,1	122,5	116,7	132,6	126,4	132,3	134,5	89,4	127,0	127,3
Trunk Thigh Left	136,5	156,0	154,7	150,5	136,5	156,0	150,5	154,7	136,5	136,1	136,4	141,9	140,2	146,7	159,9	134,7	144,7	136,8	145,6	139,7	141,6	142,8	99,6	156,8	133,4
Leg Splay Right	-0,6	-10,0	-10,0	-5,0	-0,6	-10,0	-5,0	-10,0	-0,6	10,3	10,0	-4,2	5,4	-5,8	-9,4	16,9	-5,2	-4,0	7,9	10,7	6,3	10,9	6,0	-5,7	17,1
Leg Splay Left	21,5	30,0	30,0	29,1	21,5	30,0	29,1	30,0	21,5	16,3	16,9	28,0	22,6	28,6	30,0	8,7	30,0	30,0	16,2	14,3	19,2	14,9	18,9	30,0	8,6
Thigh Rotation Right	12,9	7,5	8,0	16,4	12,9	7,5	16,4	8,0	12,9	4,2	0,8	14,5	5,5	16,5	14,1	-1,5	9,4	4,2	2,1	1,7	-2,8	-4,8	1,2	10,6	-6,6
Thigh Rotation Left	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Knee Included Right	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Knee Included Left	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Foot Calf Included Right	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0
Foot Calf Included Left	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0

Figure 4. Dreyfuss 3D results for every posture (average values among all users)

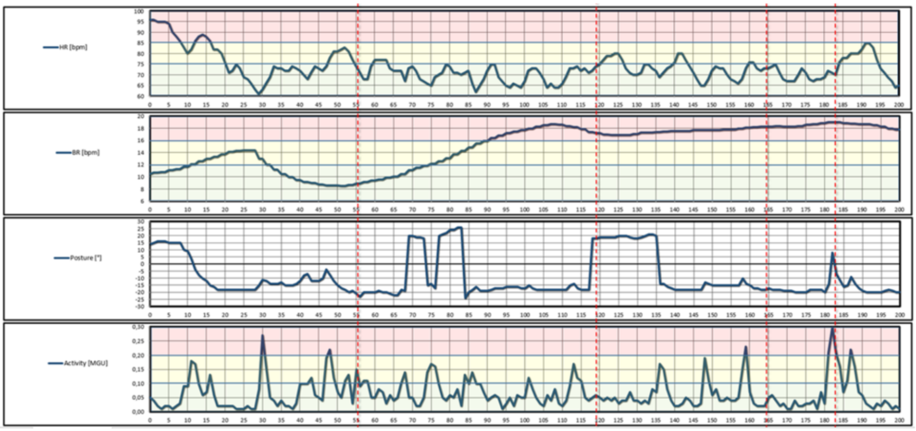

Figure 5. Physiological data collected by the biosensor (respectively HR, BR, Posture and VMU)

4. Conclusions

The paper proposes a mixed reality (MR) set-up where products are represented by both virtual and physical mock-ups, and humans are digitalized and monitored in order to easily evaluate the human-machine interaction. Such transdisciplinary approach has been applied to an industrial case study referring to tractors' cabin design optimization, developed in collaboration with CNH Industrial. The case study demonstrated that the proposed set-up validly supports human-centred design thanks to the analysis of both physical and cognitive stress of users, simulating the real operators during task execution. The main advantage is to have a precise feedback about human-machine interaction on the virtual model, before its realization to predict the design criticalities and to improve the global system design or re-design. Such a feedback will be very important for companies to reduce the time-to-market and to optimize costs as well as improving the workers' safety and satisfaction, with a great impact on the overall sustainability. Future works will focus on a more deep analysis of the human stress and the definition of a design strategy to be implemented in the company to avoid stressful conditions.

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