A Comparison Between Virtual Reality and Digital Human Modeling for Proactive Ergonomic Design

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Abstract. Proactive ergonomics can improve the overall performance and well-being of the user and has the potential to improve the product quality and reduce the cost of resources. Application of Digital Human Modeling (DHM) is a pathway for proactive ergonomics. However, DHM has the issue of fidelity and it is yet not in the level of simulating human perceptions and emotions accurately. In this study, we have proposed an ergonomics approach that is used to infuse human factor engineering (HFE) guidelines during the early design process. The approach utilizes Virtual Reality (VR), Computer Aided Design (CAD) objects, and human-subjects to proactively filter design ideas, during the conceptualization phase, before functional prototypes are built. A comparative study between full computational prototyping and mixed prototype using VR is performed by (a) designing cockpit packaging and (b) assessing human performance during a fire in cockpit emergency situation. It is found that the cockpit design based on the two prototyping strategies provide similar outcomes. However, the computational prototyping approach is more suitable in design space exploration and the mixed prototyping is more relevant for communicating design ideas. Further, it is found that the computational prototyping approach cannot simulate the change in human performance due to emergency whereas the mixed prototype is able to simulate the change in human performance due to the emergency situations.

Keywords: Proactive ergonomics · Human factor · Digital Human Modeling · Virtual Reality · Design · Prototyping · Cockpit · Emergency

1 Introduction

Incorporating ergonomics approach early in the product development not only reduces the risk of injury and discomfort but also has the potential to improve the user performance and overall production cost [1]. Despite the benefits of ergonomics, it is sometimes not clear for many companies how to apply ergonomics or Human Factor Engineering (HFE) principles early in the design process [2]. A great deal of research in the design literature shows that designers often perceive adding ergonomics into the design process with an increase in the

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workload and additional engineering constraints. Also, many believe ergonomics is not part of a designer's core job [3]. There are also few studies show that many engineers think that there is not enough time to consider ergonomics within the product design process [4].

In addition to the above limitations, there is also a significant disconnect between ergonomics theory and how it is incorporated within the design process. Specifically, there is a discrepancy between reactive and pro-active ergonomics approaches within product development. For example, the traditional reactive ergonomics design approach uses checklists which often requires the presence of a functional physical prototype and human-subject studies to assess the ergonomics performance [5]. This approach misses the opportunity to correctly utilizing the HFE within the product design. It is because physical prototypes are time-consuming and expensive to build which delays the evaluation and feedback loop. Any modification or retrofitting that are applied at late stages of the design process is time-consuming, costly to carry on, and sometimes infeasible to implement since most of the major design decisions are made early in the design process [6,7]. Hence, the traditional reactive ergonomics approach causes designers to end-up with a sub-optimal product or workplace design [8].

The problems of traditional reactive approach can be partially mitigated by proactively applying ergonomics assessments early in the design, before the products built, via computational or virtual prototyping strategies. One of the promising proactive computational approach, Digital Human Modeling (DHM), can bring the advantage of using ergonomics and biomechanics simulation tools early in the design to explore human factors issues. This approach has the potential to reduce product lead time, improve quality and increase user-performance [9–11]. DHM technology offers designers the promise of running various what-if scenarios to simulate a large variety of human-product interactions, then correct any ergonomics issues early in the design phase [12].

Although DHM approach has the advantage of providing quicker evaluations and earlier feedback to the designer, it has limitations in predicting actual human performance measures with high-fidelity [13]. Another limitation is in its inability to assess human cognitive performance accurately [14]. One way to circumvent the limitations of computational prototyping due to DHM is to use mixed-prototyping via a human-in-the-loop strategy where users are immersed in a virtual workplace or environment (e.g., via using virtual reality) and execute tasks. Immersing a real human subject into a virtual workplace can mitigate some of the fidelity limitations found in DHM such as complex task generation, posture setup, and perception.

Hence, in this paper, an early design ergonomics methodology is proposed with the goal of injecting HFE into the design process and executing ergonomics evaluations, proactively, before committing into a final design. The approach utilizes Virtual Reality (VR), Computer Aided Design (CAD) objects, and human-subjects to proactively filter design ideas, during the conceptualization phase, before functional prototypes are built. In this paper, a comparison between the two prototyping strategies (i.e., a computational prototype using DHM and a mixed-prototype using VR, CAD, and human subject) are performed by going through a cockpit packaging case study, which is focusing on ergonomics performance assessments during an emergency situation - fire in a cockpit. Performance assessments are performed using two types of prototyping strategies, and the merits and demerits of both strategies regarding fidelity, time, and cost are presented.

The rest of the paper is organized as follows. Section 2 contains a literature review on prototyping and computational prototyping strategies. Section 3 illustrates the early design ergonomics methodology presented in this paper and Sect. 4 includes the design case study. Sections 5 and 6 present the result and discussion of the case study. Finally, Sect. 7 provides the limitations and future work.

2 Literature Review

2.1 Prototyping

Prototyping is defined as an artifact that is used to replicate features of a product, service or system for evaluation and development [15,16]. In the context of human-centered design, prototyping is performed to assess the usability and ergonomics of concept ideas prior to committing a significant amount of resources such as time and money into the final design. There are various taxonomies and classifications of prototyping that exist in engineering, industrial design, and architecture literature. One of the common identifiers for many prototyping strategies is whether the prototypes are built for assessing the form or functionalities of a product [15,17]. Alternatively, Stowe et al. proposed a three-level hierarchy system to classify prototyping strategies, which is based on (a) the variety of prototypes (i.e., physical prototype, computational prototype or a mixed prototype); (b) the complexity of prototypes (i.e., whether the complete product or a partial product is built); and, (c) the fidelity of prototypes which determines how accurately the prototype replicates or mimics the final product [18]. Beyond such mainstream taxonomies, Camburn et al. stated that some of the four most frequently cited objectives behind prototyping are: refinement, communication, exploration, and active learning [19].

The brief literature reveals that prototypes can be built in various ways. From the human-centered design perspective, it is crucial to determine how the prototypes should be built and what objectives should it be able to accomplish. A physical prototype can be of high fidelity, but it is time-consuming and expensive to build which causes delays in ergonomic evaluations. In contrast, a computational prototype can be built in a shorter period of time; however, it lacks fidelity. The contradictory findings give rise to the dilemma of what prototyping strategy to follow; however, currently, there are no widely accepted guidelines to assist designers for generating ergonomics assessments [20]. Therefore, many designers rely on previous experiences and trial-and-error on various prototyping strategies to execute ergonomics analysis before products are built. The next section presents computational and mixed prototyping practices in human-centered design.

2.2 Computational Prototyping: Digital Human Modeling

There are several ways to perform ergonomic analysis computationally. This study focuses on a prototyping approach where the workplace or product representation is created using Computer Aided Design (CAD) software and ergonomic assessment is performed using Digital Human Modeling (DHM) packages. DHM is defined as a methodology to perform computational ergonomic assessment by inserting a digital manikin inside a computer or virtual environment to simulate the performance and safety of a worker. It also includes graphical visualization of humans with math and science in the background [14,21]. From the perspective of research, DHM is defined as a mathematical model to represent human behavior through a real-time computer graphic visualization in response to a minimal command input by a user [22]. DHM consists of anthropometric libraries that represent various demographic populations. These libraries enable designers to perform design decisions based on ergonomic evaluations applied to the specific populations. Some of the common ergonomic assessments include lower-back (L4/L5 - the lower 4th and 5th lumbar section) analysis, posture analysis, energy expenditure, vision, reaching zone, etc.

DHM has been used as a computational ergonomics method in various design studies including aviation, automobile, space, and health-care. Some of the recent examples that used DHM to perform ergonomic evaluations early in design are as follows. For example, Khayer et al. performed an ergonomic evaluation of manual weeding using wheel hoe to reduce work-related musculoskeletal disorders. Posture and biomechanical behavior of the workers were studied. The study revealed that a larger group of male population (50th–95th) are assuming more uncomfortable postures. Also, L4/L5 forces are found to be higher on both male and female workers [23]. Another recent study from Ford Research and Advanced Engineering presents how DHM is used to assess and design new vehicles. This study reports that using real human appraisal during new vehicle design is subjective, qualitative, and might not be accurate. Their proposed methodology includes capturing human motions and compare how human motion changes due to new designs. These motions are then used to drive the digital manikins and generate a swept volume of the corresponding body segments. The swept volumes are used to find out the minimum clearance between the human body segments vehicle components [24]. Another human motion data study uses DHM along with Kinect to automate the human engineering simulations. The study claims that simulating a human posture solely using DHM has two drawbacks. The first drawback is setting up and simulating a complex human posture is time-consuming and also the fidelity or accuracy of the posture simulation depends on the designer's expertise and knowledge in the DHM software. To minimize time and bias of the designer during posture construction and simulation, Jun et al. have automated the simulation by capturing human postures through multiple Kinects and feeding the motion data to a DHM motion compiler [25]. In a slightly different study, Irshad et al. proposed a methodology that couples DHM with function failure and human error analysis to enable ergonomic assessments early in the design process [26]. The method uses the results from the Human Error and Functional Failure Reasoning (HEFFR) [27,28] to guide designers towards choosing the appropriate DHM analysis through an iterative process. The authors conclude that while DHM enables ergonomic assessments, it also provides a means to visualize human product interactions and predict unforeseen errors early in the design process.

Although DHM has the advantage of saving time and financial commitments, it has some limitations. Chaffin pointed out that a major issue of DHM is the lack of fidelity of the ergonomic evaluation [13]. Similarly, a study by Lamkull et al. states that DHM has acceptable fidelity when simulating simple postures, but during complex task simulations DHM lacks the fidelity [29]. Another limitation of DHM is predicting the cognitive or perceptual aspects of uses. When compared to physical DHM models, cognitive methodologies and tools within the DHM domain are still in an early developing stage [14].

2.3 Mixed Prototyping: Virtual Reality

Mixed prototyping is defined as a technology that mixes both the real and virtual components of a design to assess product interactions [30]. In mixed prototyping, a workplace or a product created using CAD and projected through a virtual reality system (e.g., head-mounted display), and actual users are asked to conduct product evaluations. Virtual Reality is defined as a technology that gives objects a spatial form and provides immersive experiences to the users. Interaction with the virtual objects provides the user with an impression of immersion rather than being only an observer [31,32]. Bordegoni et al. proposed a framework for mixed prototyping which consists of two independent domains, namely, prototype and user. Both of these domains have two states of being real and virtual which give rise to four settings: (1) real user - real prototype; (2) real user - virtual prototype; (3) virtual user - virtual prototype; and, (4) virtual user - real prototype. Additionally, *real user - mixed prototype* was proposed as a hybrid setting which takes into a real person immersed in a prototype that contains virtual and physical components. These prototyping strategies were used for evaluating different types of products. Ergonomics and usability assessment were generated. It was concluded from the study that traditional physical prototypes do not allow generating both operational and emotional agents of ergonomics in a short period of time [30].

In conclusion, mixed prototypes have the advantages of assisting designers in performing ergonomics and usability assessments in a short period and has the potential to reduce the cost of prototyping. Since the workplace or product is represented virtually; thus, it also reduces the risk of injuries and stress of the user-workplace interactions [33]. However, mixed prototypes using virtual reality lacks the depth perception, haptic feedback and other multi-sensory feedback [34,35].

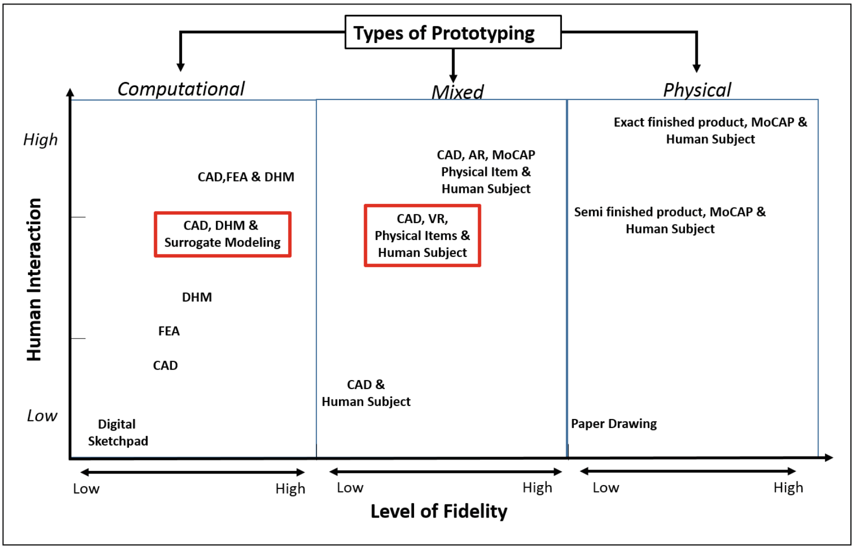

Fig. 1. Types of prototypes for designing workplace or product and assessing human performance adapted from [36]

3 Methodology

In this paper, two types of prototypes are studied namely, computational prototyping and mixed prototyping with the goal of performing (a) workplace design and (b) human performance assessments during an emergency case study. One can see that Fig. 1 illustrates various prototyping methodologies which are categorized based on their type and fidelity as shown in the horizontal axis. The vertical axis represents the level of interaction found on the product that is going to be prototyped. Figure 1 provides a partial guideline to a designer regarding how to build a prototype depending on the level of interaction of the product or workplace and the amount of fidelity desired. In this study, we evaluated two types of prototyping strategies, shown by the rectangular boxes, specifically: (1) full computational prototype created using CAD, DHM, and surrogate modeling technique; and, (2) a mixed prototype created using CAD, VR, physical objects and human subjects. The following sections describe how each of the prototypes is built to do workplace design and performance assessment during an emergency situation.

3.1 Computational Prototype

Workplace or Product Design: The computational prototype utilizes a surrogate model to express human performance as a function of some design variables of the workplace or product. This surrogate model is then explored and optimized to find configuration or design of the workplace that gives optimal human performance. The computational prototyping method starts with creating the CAD model that represents the workplace or product, then importing it to a DHM (Siemens JACK [37]) for ergonomics analysis. Next, the designer needs to know what design variables of the workplace or product affect the designer's performance. So, several probable design variables are selected and varied to find the change in human performance. Once the design variables are identified, several workplaces or product concepts are created by varying design variables. Later, the corresponding human performance for each concept is measured quantitatively. This procedure allows the creation of a surrogate model which models the human performance to design variables of the concepts using mathematical equations. The surrogate model can be explored and solved to identify the configuration, i.e., design variables of the workplace or product that gives the optimal human performance. This computational prototype is explained in detail in Ahmed et al. [38].

Performance Assessment: The computational prototype is also used to simulate the performance of a user/designer during an emergency situation. Similar to the workplace design using computational prototype, a CAD model of the workplace or product is created and imported into DHM. Additionally, a sense of the emergency situation is created by inserting elements of emergency such as fire, smoke, alarm, light etc into the workplace. A digital manikin is inserted into the workplace and his performances are measured both during an emergency situation and non-emergency situation. In this paper, performance is assessed by identifying the changes in posture for a sequence of reaching task due to emergency situation compared to a non-emergency situation. Only upper body posture analysis is performed through Jack's comfort assessment tool.

3.2 Mixed Prototype

Workplace or Product Design: As shown in Fig. 1, the mixed prototype consists of a CAD model of the workplace or product, virtual reality (HTC Vibe [39]), physical objects and human subject. In order to have consistency, the same CAD model of the workplace or product is used in both the prototypes. The CAD model is imported to SimLab virtual reality [40] which is a platform that converts the workplace or product into an immersive virtual world through VR. The attribute of interacting virtual objects in VR is exploited in this study so that the designer can design the workplace or product by changing the configuration of the virtual objects in such a way that ensures optimal performance. This approach would include direct manipulations (such as moving, rotating or changing spatial configuration of the virtual product) in a VR environment according to designer's or customer's own ergonomic requirements. Though the designer can interact and design the workplace according to the designer's ergonomic requirement, there is a limitation on quantifying the ergonomic assessment. Since the performance cannot be quantitatively measured in SimLab so the newly designed workplace or product is imported to DHM (JACK) and the performance is measured quantitatively. Similar to having the same CAD model in both types of prototypes, the same anthropometric manikin and human subject is used in both prototypes respectively to have consistency. An Asian-Indian human subject and manikin of 168 cm height and 73 kg weight are used respectively.

Performance Assessment: The mixed prototype is also used to simulate and compare human performances during an emergency situation and a non-emergency situation. Similar to the computational prototype, a sense of emergency is instilled in the workplace by putting elements of emergency such as fire, smoke, alarms, lights etc. The human subject performs the same sequence of the task as the digital manikin performed in the computational prototype. The performance is assessed by identifying the difference in reaching task posture arises due to emergency and non-emergency situations. The postures of the human subject can not be measured through the mixed prototype setup. So Microsoft Kinect is used as a marker-less motion capture device that is connected to Jack for quantitative posture analysis. An upper body posture analysis is performed in both types of prototypes using Jack's comfort assessment tool.

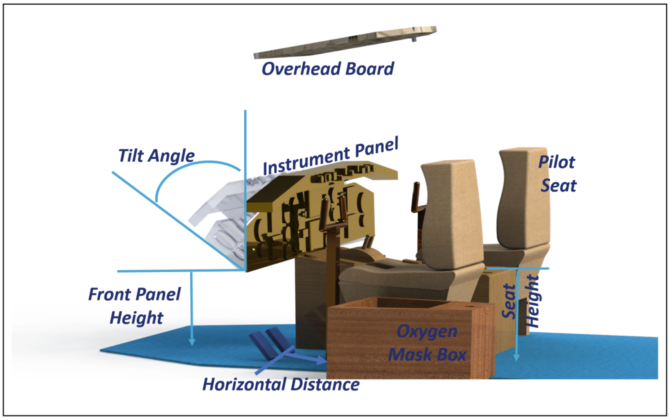

Fig. 2. CAD of Boeing 767 Cockpit

Table 1. Design variables and design objectives

Design variables	Ranges
Instrument Panel Height	47–80 [cm]
Instrument Panel Tilt Angle	0–30 [degree]
Horizontal Seat Distance	30–55 [cm]
Vertical Seat Height	34–53 [cm]
Design objectives	**Minimize reach gap & Minimize vision obscuration**

4 Case Study

Cockpit packaging and fire in the cockpit of a Boeing 767 is taken as a case study to demonstrate the methodology of designing for ergonomics and simulating human performance in an emergency situation using both the computational and mixed prototyping. The aviation sector is widely known for utilizing human factors engineering guidelines in order to improve pilot performance and reduce errors. Also, the advent of smart technologies such as touch displays and digitized controls causes the cockpit control area to undergo changes in future models and variants. The new layouts and designs should be evaluated from an ergonomics perspective to assess human performance. In this design case study, the height and tilt angle of the instrument panel and the horizontal and vertical distance of the pilot seat are considered as design variables as shown in Fig. 2. The explanation for selecting these design variables are given in [38].

The objective in cockpit packaging design is to improve the reachability to the instrument panel and improve the pilot's vision through the windshield. The ranges of each design variable and the objectives of the design are shown in Table 1. The maximum and minimum ranges of the design variables are extracted from aviation databases corresponding to civilian aircraft [41].

The objective in simulating human performance during an emergency situation is to identify which types of prototypes can accurately capture the pilot's posture during an emergency situation. During a fire in the cockpit, the pilot goes through a series of tasks such as reaching oxygen mask box on the left console, reaching for the instrument panel, and reaching auxiliary power on the overhead board. Details about the fire in Boeing 767 cockpit is given in [36]. Simulating these reaching task using both the prototypes and identifying postural differences will let designers understand which type of prototypes is better suited to prototype emergency situations. Sections 4.1 and 4.2 discusses how these two prototypes are used for cockpit packaging design and human performance assessment during the fire in cockpit emergency situations.

4.1 Computational Prototype

The CAD model of a Boeing 767 cockpit as shown in Fig. 2 is imported into DHM, i.e. Siemens JACK, as shown in Fig. 3(a). A digital manikin which represents the designer's anthropometry is inserted in the cockpit, and ergonomic assessment of instrument panel reachability and vision obscuration analyses are performed by changing the design variables. Details about the ergonomic assessment performed in DHM are provided in the Result Section. Additionally, performance (e.g., posture analysis of the designer/pilot during an emergency situation and non-emergency situation) is evaluated using JACK's comfort assessment tool. Figure 3(b) shows a spherical bubble in the cockpit which represents the smoke and fire produced during the emergency situation. Human performance assessment is assessed by comparing the postures for reaching (a) oxygen mask, (b) instrument panel, and (c) overhead board during an emergency and non-emergency situation.

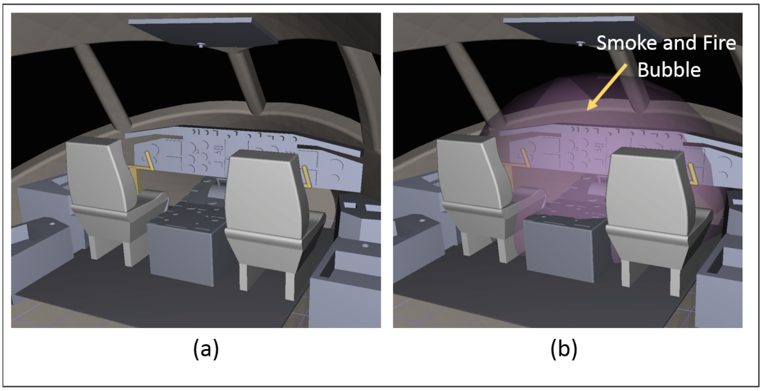

Fig. 3. Boeing 767 CAD imported to Jack for ergonomic design and performance assessment during emergency situation

4.2 Mixed Prototype

Similar to the computational prototype, the CAD model of a Boeing 767 shown in Fig. 2 is imported into SimLab as shown in Fig. 4(a). The designer then puts the HTC Vive VR headset on to get immersed inside the CAD cockpit. In the immersive virtual cockpit, the designer interacts with the instrument panel and pilot seat using the wand (hand control) by translating and rotating the objects according to his ergonomic requirement. Once the designer finalizes the cockpit arrangements in VR, the final cockpit configuration is exported to JACK to measure the performance of reachability and vision quantitatively. Figure 4(b) shows the fire in the cockpit scenario by placing a dynamic fire and smoke inside the CAD model using SimLab software. This approach replicated the fire in the cockpit emergency and the designer/pilot's performance is assessed by measuring the upper-body postures as discussed in the computational prototype. The postures of the designer are captured using Kinect and posture angles are measured using JACK.

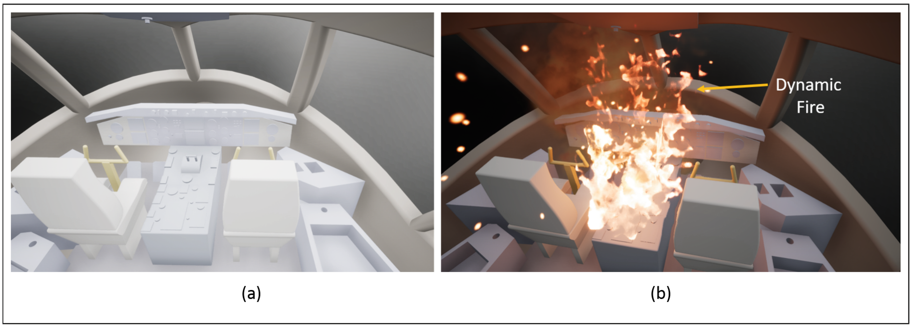

Fig. 4. Boeing 767 CAD imported to SimLab for ergonomic design and performance assessment during emergency situation

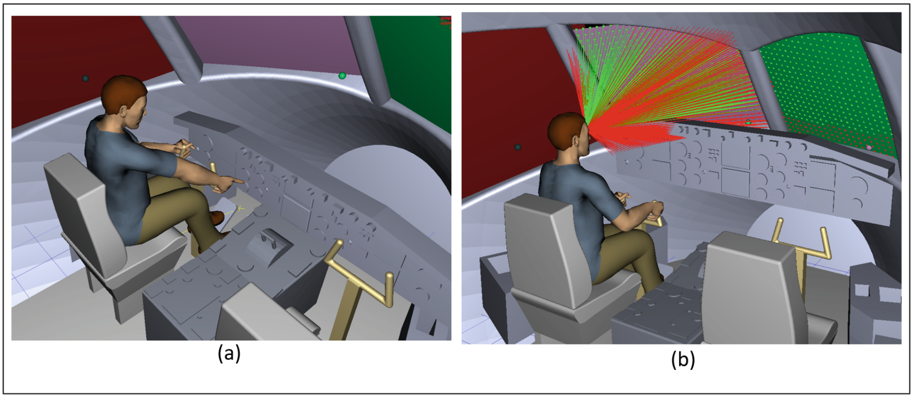

Fig. 5. Cockpit design using computational prototype (Color figure online)

5 Result

5.1 Cockpit Design Using Computational and Mixed Prototype

In the computational prototype, multiple cockpit configurations are created by changing the design variables. In each cockpit configuration, the same manikin is inserted and ergonomic assessment of reachability and vision is performed as shown in Fig. 5. Figure 5(a) shows the manikin is reaching towards the instrument panel and the reach gap between the index finger and instrument panel is measured. Similarly, vision obscuration is measured as shown in Fig. 5(b). The green rays show visibility and red rays show obscuration. The reach gap and vision obscuration for each cockpit configuration are used to create a surrogate model. The surrogate model is explored and optimized to identify the minimum reach gap and minimum vision obscuration. The surrogate modeling technique is described in Ahmed et al. [38].

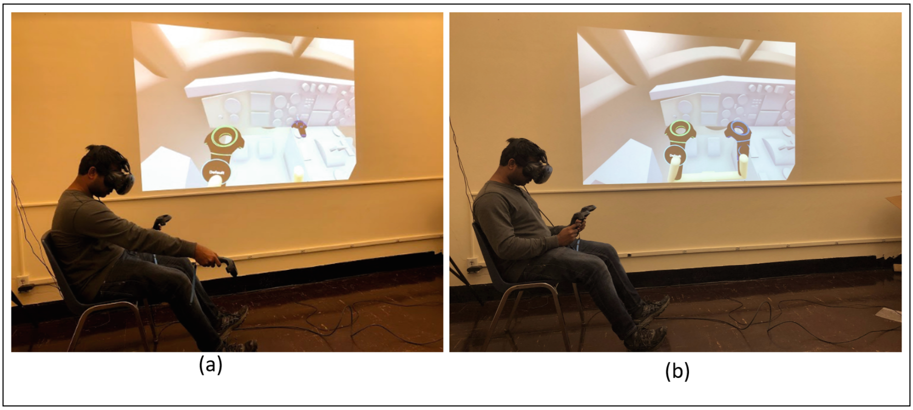

Fig. 6. Ergonomic evaluation using mixed prototype

Furthermore, the mixed prototype is used to assess the reachability and vision obscuration as shown in Fig. 6(a) and (b) respectively. The designer is immersed in the virtual cockpit where he can position himself in the pilot's seat and sits on a physical chair. From the seated position, the designer can use the wand to do a reach assessment and move his head around for vision obscuration assessment. Also, the designer can interact with objects to create new cockpit configurations. Figure 7 shows the designer is translating and/or rotating the instrument panel according to his ergonomic need. The designer can create an optimal configuration of the cockpit by spatial manipulation of the pilot seat and instrument panel. In this study, the designer created six optimal cockpit configurations: two configurations that give minimum reach gap, two configurations that give minimum vision obscuration, and two configurations that provide a balance between the two objectives. These optimal configurations are then exported back to JACK to get a quantitative measurement of reach gap and vision obscuration.

Figure 8 shows a plot of percentage vision obscuration versus reach gap for both types of prototypes. The surrogate model of the computational prototype is explored and used to create the plot. Some of the reach gap values are negative which implies that the manikin is positioned in such a way that the index finger goes beyond the instrument panel when the hand is stretched. The reach gap and vision obscurations obtained from the six cockpit configurations designed via mixed prototype is superimposed on Fig. 8 for comparison purpose. One can see that the ergonomic assessment from mixed prototype closely overlaps with the ergonomic assessment obtained from the computational prototype. An independent sample Student's t-test is used to compare the ergonomic assessment obtained from the two prototypes. The results are given in Table 2. The p-values are greater than 0.05 which suggest that mean ergonomic values or reach gap and vision obscuration obtained from the two prototypes are not significantly different, or in other words, ergonomic assessments from the two prototypes are close to each other.

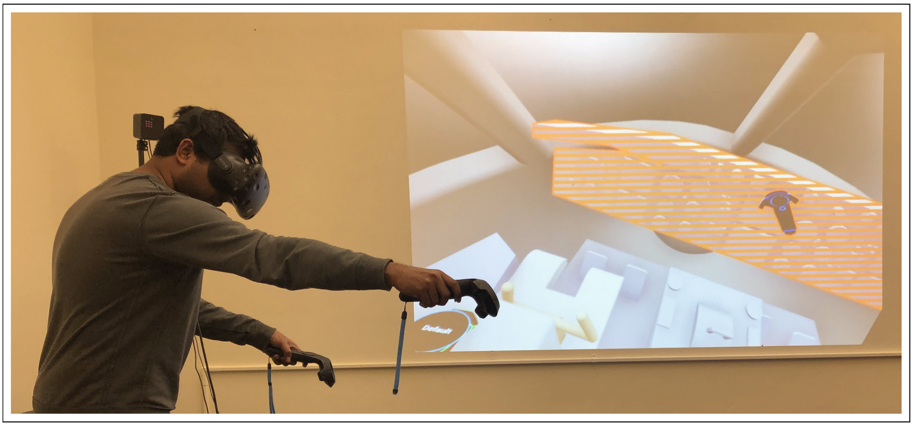

Fig. 7. Interacting with objects to design the cockpit using mixed prototype

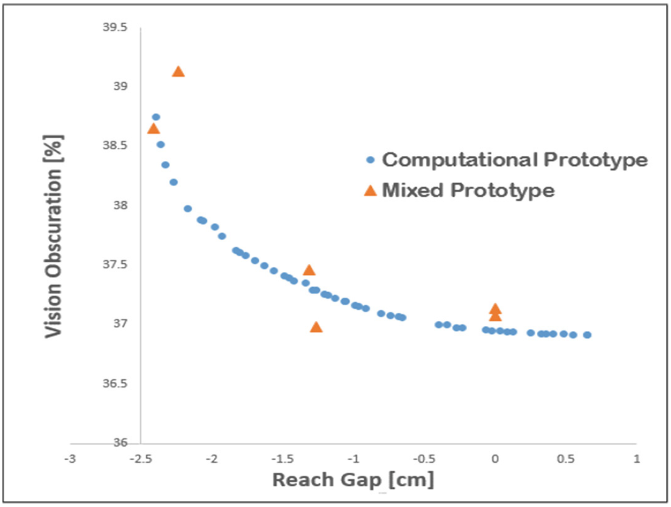

Fig. 8. Cockpit design comparison between computational and mixed prototype

5.2 Posture Assessment in Emergency Situation Using Computational and Mixed Prototype

As mentioned in Sects. 4.1 and 4.2, posture assessment for reaching (a) oxygen mask, (b) instrument panel and (c) overhead panel during non-emergency and emergency situation are performed using both types of prototypes. The emergency situation of fire in the cockpit is created by placing a smoke bubble in JACK and a dynamic fire in SimLab as shown in Figs. 3(b) and 4(b) respectively. It is observed in the JACK, i.e., the computational prototype that there is no posture change of head and upper arm angle, due to the emergency situation. However, in the mixed prototype, the designer showed different postures for the reaching task during an emergency situation as compared to non-emergency situations. The postures during emergency situation using mixed prototype are

Table 2. Statistical analysis between computational and mixed prototyping

	Reach gap		Vision obscuration	
	Computational	Mixed	Computational	Mixed
N	50	6	50	6
Mean	−0.941	−1.203	37.332	37.740
SD	0.918	1.042	0.450	0.917
F-value	0.014		11.119	
t -value	0.588		−1.072	
p-value	0.578		0.330	
CI	−0.828 to 1.352		−1.368 to 0.553	

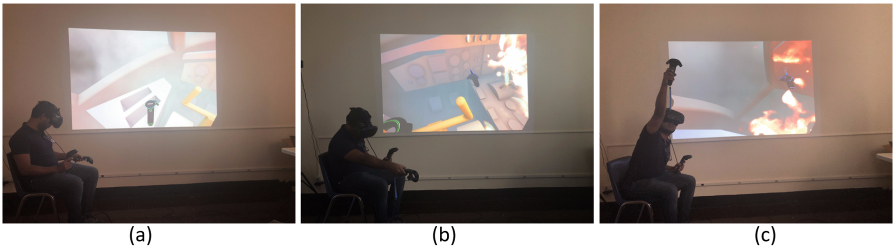

Fig. 9. Posture assessment during emergency situation using mixed prototype

shown in Fig. 9. The reaching task is repeated three times, and the average posture angles for both the prototypes during non-emergency and emergency situation is shown in Table 3. This table shows that the posture angle in JACK is exactly the same whether there is an emergency or not but the postures identified through mixed prototype is different. The Intra-Class Correlation (ICC) test is performed to statistically analyze the body segment joint angles for emergency and non-emergency situations. The ICC test measures how strongly two groups correlate to each other. The ICC value ranges from 0 to 1. A value of 0 means no correlation and value of 1 shows perfect correlation [42–44]. In this study, the ICC value is 0.656, which is a fair correlation. This value suggests that the posture of the human subject during an emergency situation is not exactly equal to that of during non-emergency situation.

Table 3. Posture analysis and intra-class correlation test between non-emergency and emergency situations

Reach	Body segments	Computational		Mixed	
		Non-emergency posture angle	Emergency posture angle	Non-emergency posture angle	Emergency posture angle
Oxygen mask	Head	30.2	30.2	0.9	5
	Upper arm	3.8	3.8	5.6	2.3
Instrument panel	Head	17.6	17.6	12.7	6.5
	Upper arm	55.2	55.2	33.5	18.5
Overhead board	Head	−4.9	−4.9	−0.15	2
	Upper Arm	125.4	125.4	36	16
ICC		N/A		0.656	
CI		N/A		−0.04 to 0.941	
Sig.		N/A		0.037	

6 Discussion

This study compared the ergonomic design and human performance assessment capabilities during an emergency of a cockpit fire by using two types of prototypes namely, a full computational prototype and a mixed prototype. The methodology presented in this study is illustrated by cockpit packaging design and posture assessment during a fire in the cockpit situation. The cockpit packaging design based on the ergonomic assessment outcomes of the reach gap and vision obscuration when using the computational prototype and mixed prototype are found to be close to each other as shown in Fig. 5 and Table 2.

Although the ergonomic assessment resulted in relatively similar outcomes, the time spent and resources allocated during a design case study for each prototype is significantly different. For example, the computational prototype requires the creation of multiple cockpit configurations according to Latin Hyper Cube Sampling (LHS) method and then performing ergonomic simulation in each of the configurations. It is estimated that it takes around 5 min for an expert DHM user to perform each simulation. Thirty cockpit configurations are created using LHS; thus, it adds up to around 150 min. Furthermore, surrogate modeling and optimization techniques are used to identify the cockpit configurations which takes an additional 200 min for a programmer/coder. So in total, the computational prototype takes a total of 320 min. Also, the cost of the software license for JACK and MATLAB or other programming software adds to the overall cost of resources used on the computational prototype.

On the other hand, the mixed prototype is created using SimLab and HTC Vive and Microsoft Kinect which are less resource intensive as compared to the computational prototype. There are only six cockpit configurations created using mixed prototype which is sufficient to replicate the result from the full-computational prototype. Each cockpit configuration takes approximately 7 min in SimLab, and an additional 5 min is required in Jack to generate each quantitative assessment, which adds up to a total of approximately 72 min. Furthermore, the SimLab educational license is free for two years and HTC Vibe costs around 500 USD. Therefore, the mixed prototype produces similar results to the computational prototype with much fewer resources. It should be noted that the cost of the CAD model and stipend for the designer is not included in this analysis as these two are present in both types of prototypes.

In addition to cockpit packaging design, posture assessment during an emergency situation is also simulated using these two prototypes. Table 3 shows that the comparison between the two prototypes in terms of posture assessments during emergency situations. The computational prototype using JACK is unable to simulate the changes in the posture angles due to fire and smoke in the cockpit. It is because, given that the starting and initial points are the same, JACK always uses the same inverse kinematic algorithm to simulate the posture. Hence, it shows no change of posture due to the fire and smoke in the cockpit. However, the mixed prototype is able to capture the differences in the posture angles due to fire in the cockpit emergency. It is because the fire and smoke presented in the cockpit hinders the vision of the designer and the sense of emergency creates an urgency. These two effects cause the designer to attempt reaching postures that are different than that of during non-emergency situation.

Although the mixed prototype is less resource intensive and generates reach gap and vision obscuration results similar to the computational prototypes, it has several shortcomings. First, the result obtained from mixed prototype carries subjective input or biased opinion of the designer. Human subjects/designers of the same anthropometric properties may create different outcomes due to their subjective ergonomic requirements or perceptions. Second, the SimLab used in mixed prototyping strategy does not generate quantitative assessment. The six cockpit designs generated in the mixed prototyping is exported to JACK for quantitative assessment of the reach gap and vision obscuration. Third, the number of cockpit concept design generation using mixed prototype is limited and depends on the designers. This makes the mixed prototyping approach inefficient in design space explorations. Whereas, the computational prototype is efficient in terms of the design space exploration and generating concepts that give an optimal human performance when coupled with the optimization technique. In contrast, because of the subjectivity associated with mixed prototyping, it can not be coupled with optimization techniques for measuring quantitative human performances.

As found in the literature, Camburn et al. stated about the different objectives of building prototypes [19], the computational prototype can be used for the objective of design exploration and the mixed prototype can be used for communication purposes. The mixed prototyping strategy is less resource intensive and the designer feels immersed in the design so it can be used for effectively and efficiently communicating design ideas with other design teams and users or customers. On the other hand, the computational prototyping strategy is resource intensive and can create numerous design concepts so it can be used for design exploration purposes. Therefore, the two types of prototypes have their own merits and demerits that can complement each other, so both of them should be used according to the desired objectives.

7 Limitations and Future Work

One of the major limitations of this methodology is the lack of validation. Neither the computational prototype nor the mixed prototype has been validated. Validation can be done by comparing the result obtained from this study with the designs created using physical prototype and human subjects. Some other limitations include using the designer as the only human subject to design the cockpit using virtual reality. This study mainly serves as a proof of concept where the designer is used as one human subject to conduct a pilot study. Incorporating multiple human subjects to design the cockpit and comparing with the computational prototype is another avenue for a future study. Another limitation is the low fidelity of the CAD model of the cockpit and the low fidelity of Microsoft Kinect used as a motion capturing device. Improving the fidelity of the CAD model and using a marker-based motion capture device can give a deeper insight into the cockpit design and human posture assessment during a fire in the cockpit emergency situation.

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