Ergonomic Design of a Main Control Room of Radioactive Waste Facility Using Digital Human Simulation

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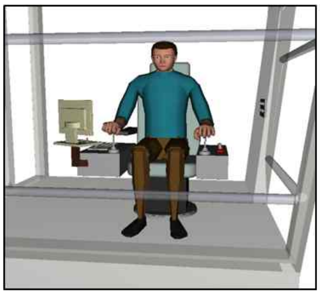
The present study evaluated a preliminary main control room (MCR) design of radioactive waste facility using the JACK® digital human simulation system. Four digital humanoids (5th, 50th, 95th, and 99th percentiles) were used in the ergonomic evaluation. The first three were selected to represent 90% of the target population (Korean males aged 20 to 50 years) and the last to reflect the secular trend of stature for next 20 years in South Korea. The preliminary MCR design was assessed by checking its compliance to ergonomic guidelines specified in NUREG-0700 and conducting an in-depth ergonomic analysis with a digital prototype of the MCR design and the digital humanoids in terms of postural comfort, reachability, visibility, and clearance. For identified design problems, proper design changes and their validities were examined using the JACK. A revised MCR design suggested in the present study would contribute to effective and safe operations of the MCR as well as operators' health in the workplace.

INTRODUCTION

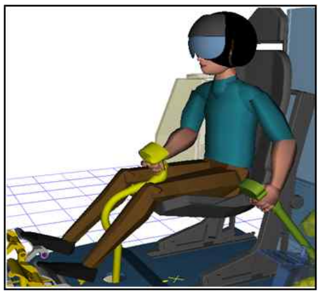
A radioactive waste facility (RWF) is a facility for managing radioactive waste which is usually by-product of nuclear power generation and other applications of nuclear fission or nuclear technology, such as research and medicine. Most Radioactive waste has been charged in a temporary facility in nuclear power plants (NPP) in South Korea, so the Korean government has planned to establish an RWF by the year 2012 in Gyeongju considering the radioactive waste saturation of the temporary facility projected in the future (KRMC, 2009).

A main control room (MCR) of the RWF needs to be considered with ergonomic aspects at the initial design stage for effective monitoring of operators and reduction of development cost. Hwang et al. (2009) analyzed three usability issues (operating interface of the display and controls in the MCR, usability of procedures, and layout of the MCR) through ergonomic evaluation of the MCR. Ku et al. (2007) evaluated and analyzed the MCR of the NPPs (unit-1, 2, 3, and 4 of the Kori NPP, unit-1, 2 of the Yeonggwang NPP) applying with ergonomic evaluation checklist as part of the periodic safety review (PSR). The evaluation of developed MCR is effective for analyzing design improvements, but on the other hand, the development of an improved MCR needs considerable time and cost. Therefore, the ergonomic evaluation at the initial design stage is needed for effective MCR design and development.

Digital human simulations (DHS) using humanoids have been used for ergonomic design of the workplace. Lee et al. (2005) and Park et al. (2008) carried out ergonomic evaluations using DHS and analyzed design improvements of the overhead crane and the helicopter cockpit respectively (Figure 1). Ergonomic design and evaluation using virtual mockups in DHS at initial design stage have been recommended as a useful method for effective retrenchment of development period and cost (Chaffin, 2005; You, 2007).



(a) Overhead crane



(b) Helicopter cockpit

Figure 1. Ergonomic evaluation using digital human simulation

The present study evaluated preliminary designs of the MCR of the RWF and analyzed design improvements. 3D virtual mockups of the MCR of the RWF were developed for use of DHS. We used JACK® for DHS and generated four representative human models (5th, 50th, 95th, and 99th percentiles) considered with the anthropometric data of Size Korea (2004) and secular trend of stature over the next 20 years. In this study, the preliminary designs of the MCR of the RWF were evaluated applying with 4 ergonomic aspects (postural comfort, reachability, visibility, and clearance) and were analyzed to determine design components and improvement direction.

METHODS

Representative Human Models

Four representative human models considered with accommodation percentage of 90% (5th ~ 95th percentiles) for the target population and secular trend of stature over the next 20 years were generated for ergonomic evaluation using DHS. The target population consisted of male aged 20 to 50 was determined considering workforce planning in the MCR of the RWF. Three representative human models (5th, 50th, and 95th

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percentiles) which can accommodate Size Korea (2004)'s anthropometric data (n = 1,992) of 90% were generated. Additionally, a representative human model having 99th percentile (same as 95th percentile over the next 20 years) which reflected three characteristics (domestic stature growth of male, international stature growth of male, and conservative estimation of stature) for consideration of secular trend. In the last 25 years (from 1979 to 2004 year), stature of Korean male has grown as 4.4 cm (Figure 2; Size Korea, 2004). On the other hand, secular growth has been reported that there are differences among nations according to economic conditions and nutrition (Roche, 1995). For example, secular growth of Korea (GNP: $ 9,287) was 1.65 cm in the last 10 years, while secular growth of Japan (GNP: $ 42.657; 4.5 times bigger than Korea's) was 1.32 cm. Finally, we applied a conservative secular growth to meet the utmost target accommodation percentage (90%) of the MCR of the RWF in the next 20 years, based on domestic and international stature growth.

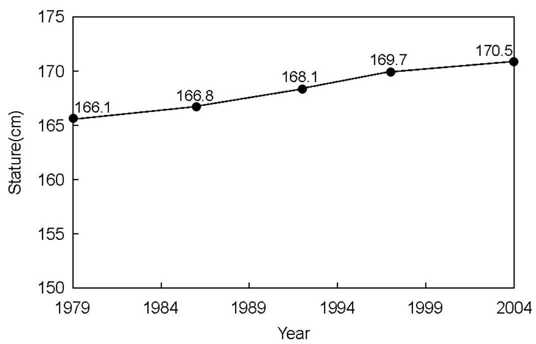


Figure 2. Stature growth trend of male aged 20 ~ 50 (Size Korea, 2004)

Humanoids in the JACK were generated through input of body sizes of generated representative human models as shown in Figure 3. In the JACK, input of 27 body sizes is needed to generate a humanoid; however Size Korea (2004) provides only 24 body sizes of them. So the present study applied with 24 body sizes provided by Size Korea (2004), the other 3 body sizes (hand breadth, head length, and thumb-tip reach) were estimated using JACK's regression equations based on 24 body sizes.

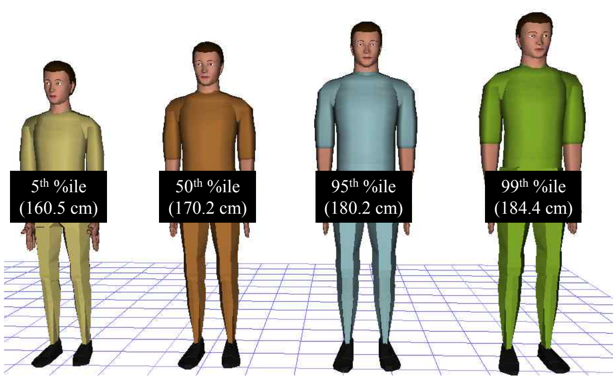
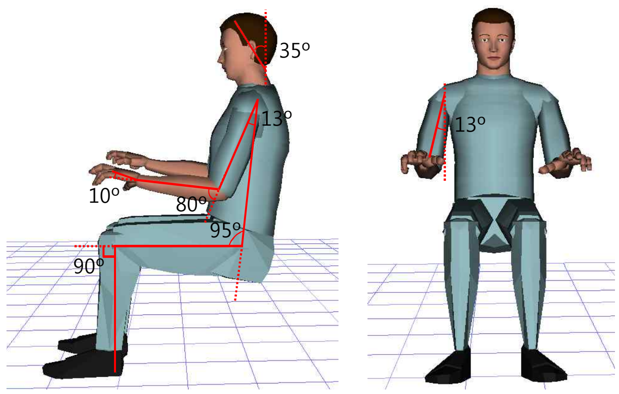


Figure 3. Generated representative human models

Reference Posture for Evaluation

The present study established an operators' monitoring posture referring to existing studies related to computer workstation postures for DHS evaluation as shown in Figure 4. The existing studies observed and analyzed reference postures at computer workstation (ANSI/HFES, 2007; Chaffin and Andersson, 1984; Grandjean et al., 1983; Salvendy, 1987). In this study, the reference posture for evaluation as shown in Figure 4 was chosen considering the operator's posture, similar to postures at a computer workstation, for monitoring tasks in the MCR of the RWF. For example, the degree of shoulder abduction was determined as 13°, which is a median degree provided by Chaffin and Andersson (1984)'s recommended range (0 ~ 25°).



(a) Side view (b) Front view

Figure 4. Reference posture of operators in the MCR

Ergonomic Evaluation Criteria

The present study established a relationship matrix between four ergonomic evaluation criteria and seven design components in the MCR (Table 1). Ergonomic evaluation criteria were determined as postural comfort, reachability, visibility, and clearance which were used in the existing DHS studies (Bowman, 2001; Nelson, 2001; Park et al., 2008). Selected ergonomic evaluation criteria were selectively applied with target design components. For example, Table 1 shows that console being seated by the operator was evaluated using postural comfort and clearance, and large display panel (LDP) providing information about the RWF was analyzed using postural comfort and visibility.

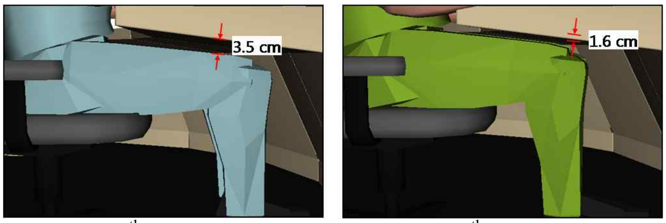
The design components of the MCR of the RWF were evaluated using NUREG-0700 design guideline. NUREG-0700 design guideline (O'Hara et al., 2002) provides ergonomic design parameters of each design component in the NPP. For example, according to NUREG-0700, the console's clearance should provide adequate height, depth, and knee clearance for the 5th to 95th percentile adults, LDP's visibility should permit operators at the consoles a full view of all display panels, and LCD's vertical viewing angle of visibility should not be more than 20° above and 40° below the operator's horizontal line of sight.

Table 1. Relationship matrix between ergonomic evaluation criteria and design components (O: related, X: not related)

No.	Design component	Postural comfort	Reach-ability	Visib-ility	Clear-ance
1	Console	O	X	O	O
2	Large display panel (LDP)	O	X	O	X
3	LCD	O	X	O	X
4	Security access control sub-console	O	O	X	X
5	CCTV master control rack	O	O	X	X
6	Main fire control panel	O	O	X	X
7	Printers	O	O	X	X

RESULTS

In this study, we show ergonomic evaluation results of three major design components (console, LDP, and LCD) of the MCR of the RWF. Console's minimum clearance which was analyzed as 1.6 ~ 6 cm for 4 humanoids was adequately evaluated in terms of the NUREG-0700. Minimum clearance was calculated as the least distance between operator's leg and console. The more body sizes of humanoid increase, the more clearance of console decrease. For example, Figure 5 shows that 95th and 99th percentile's minimum clearance were 3.5 cm and 1.6 cm respectively.

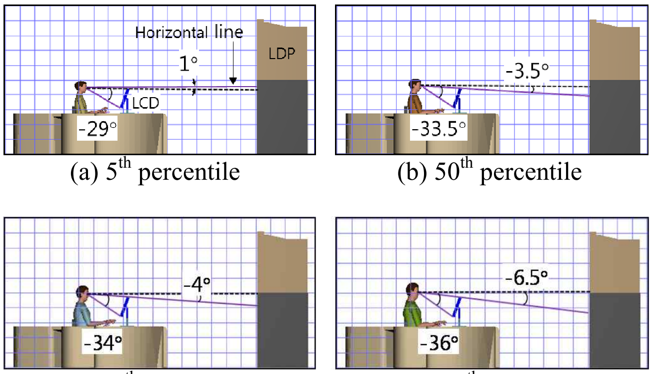


(a) 95th percentile (b) 99th percentile

Figure 5. Clearance of the console for operator's upper leg

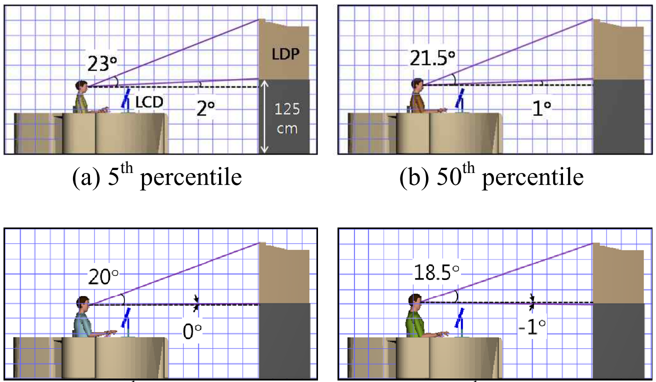
LCD's vertical gaze range (VGR) was analyzed satisfying with the NUREG-0700 design guideline. LCD's VGR was calculated as humanoid's vertical viewing angle when the humanoid at the reference posture monitored the top and bottom of LCD. For example as shown in Figure 6, 5th and 95th percentile's LCD's VGR (5th percentile: - 29 ~ 1°, 95th percentile: - 34 ~ - 4°) were analyzed satisfying with - 40 ~ 20° recommended by the NUREG-0700 design guidelines.

LDP's VGR could cause postural discomfort when operators monitor for a long time because of the higher than horizontal line (0°). LDP's VGR was calculated as humanoid at the reference posture monitored the top and bottom of LDP over LCD having 125 cm. For example as shown in Figure 7, 5th percentile's LDP's VGR (2 ~ 23°) was adequately evaluated because of being formed over the top of LCD (Figure 7.a).



(a) 5th percentile (b) 50th percentile
(c) 95th percentile (d) 99th percentile

Figure 6. Vertical gaze analysis: LCD



(a) 5th percentile (b) 50th percentile
(c) 95th percentile (d) 99th percentile

Figure 7. Vertical gaze analysis: LDP (125 cm)

LDP's VGR of all humanoids (- 1 ~ 23°) met the NUREG-0700 design guideline that LDP should permit operators at the consoles full view (Figure 7). However, the current design of LDP which was formed over horizontal line (0°) could cause fatigue and postural discomfort during the long monitoring task according to existing studies with regard to recommended display gaze range (- 26 ~ - 2°, Grandjean et al., 1983; - 56 ~ - 1°, Kim et al., 1991; - 40 ~ 20°, O'Hara et al., 2002).

To improve LDP's VGR through decrease of LDP's height, it was analyzed that LCD' height should be decreased along with LDP's height. It was found that LDP's VGR could improve through reduction of LDP's height, however interference between LDP's and LCD's VGR could appear as shown in Figure 8. To solve this interference effectively, we designed a groove located into console as shown in Figure 9. In case LDP's height became 115 cm through the LCD installation groove, having height of 10 cm, LDP's VGR was improved as - 3 ~ 19° (Figure 10). As a result, improved LDP's VGR in this study became lower than the existing LDP's VGR (- 1 ~ 23°). For example, LDP's VGR of 5th percentile was improved from 2 ~ 23° to 0 ~ 19°. Meanwhile LCD's VGR (- 31 ~ 2.5°) was satisfied with the NUREG-0700 design guideline (- 40 ~ 20°) at the improved design.

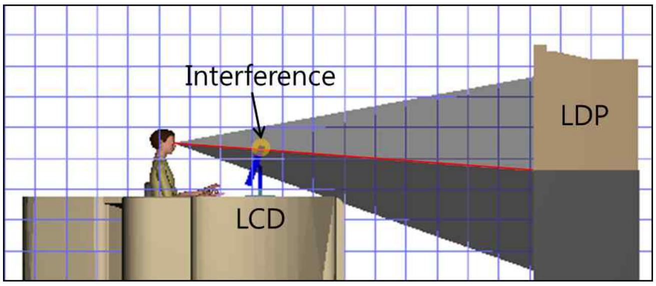
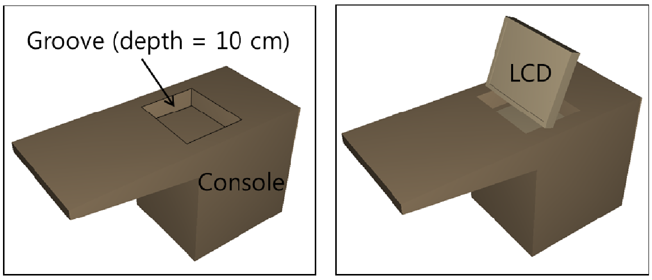
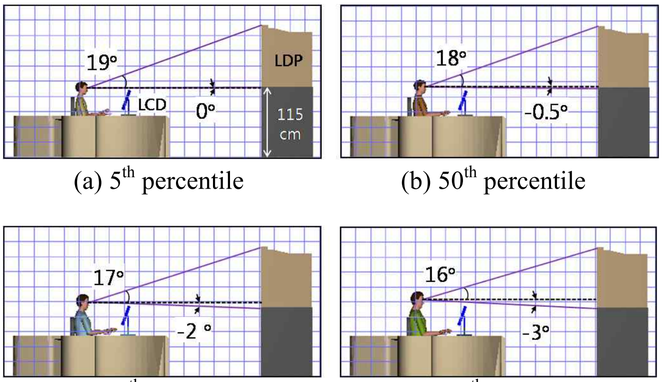


Figure 8. Vertical gaze interference between LCD and LDP



(a) LCD installation groove (b) Installed LCD

Figure 9. Installation groove of LCD in console

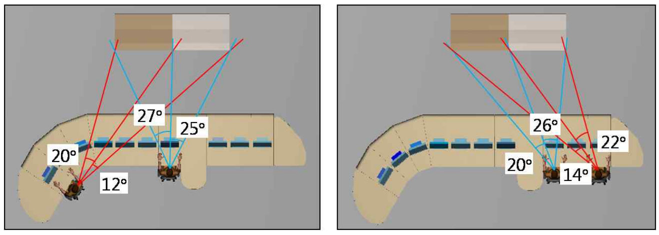


(a) 5th percentile (b) 50th percentile

(c) 95th percentile (d) 99th percentile

Figure 10. Vertical gaze analysis: improved LDP (115 cm)

LDP's horizontal gaze range (HGR) was analyzed satisfying with the NUREG-0700 design guideline that operator's HGR should be within 30° from center of LDP. The MCR of the RWF has planned to be managed by an operator (operation of 7 consoles left) and a supervisor (operation of 3 consoles right) as shown in Figure 11. LDP's HGR was calculated as a horizontal gaze interval when both the operator and the supervisor monitored LDP's left and right points from center of LDP. The operator's and the supervisor's HGR were analyzed as 12 ~ 27° and 14 ~ 26° respectively, according to assigned console position.



(a) Operator (b) Supervisor

Figure 11. Horizontal gaze analysis: LDP

DISCUSSION

The present study analyzed the preliminary design of the MCR of the RWF through ergonomic evaluation considered with the NUREG-0700 design guideline in digital environment using the JACK. The evaluation of the MCR of the RWF was conducted considering four ergonomic aspects (postural comfort, reachability, visibility, and clearance), NPP design guidelines provided by the NUREG-0700, and references related to ergonomic computer workstation design. With regard to the design components that need to be improved through digital human simulation, ergonomic solutions were developed and evaluated to analyze improvement effects. The improved preliminary design in this study can contribute to the MCR design of the RWF in the future.

The present study applied to representative human models to make humanoids in JACK considering Korean anthropometric characteristics and secular trend of stature. Three representative human models were generated considered with demographic characteristics of the operator in the MCR of the RWF to accommodate 90% (5th ~ 95th percentiles) of male aged 20 to 50 of Size Korea (2004). Additionally, one representative human model having 99th percentile for the next 20 years was generated to reflect secular trend of operator's stature based on Korean stature from the years 1979 to 2004.

The present study used estimated body sizes in terms of three anthropometric variables (hand breadth, head length, and thumb-tip reach) provided by the JACK, however these variables were highly correlated with other variables. Meanwhile the JACK generates a humanoid through input of 27 body sizes; body sizes not inputted were automatically estimated. The present study conducted post hoc analysis through stepwise regression analysis (p_{in} = 0.05, p_{out} = 0.1) in terms of the missing 3 anthropometric variables and other 24 anthropometric variables using US Army anthropometric data (Gordon et al., 1988). As a result, regression equations of the missing 3 anthropometric variables had a high adjusted coefficient of multiple determinations (adj. R^2 = 52%, hand breadth; 83%, head length; 84%, thumb-tip reach).

The present study established the reference posture for evaluation based on computer workstation posture provided by the existing studies. However, the reference posture at the MCR in this study could be different with recommended postures at a computer workstation (only for one display) because more than two displays (LDP and LCD) have been installed in the MCR. Therefore, consideration of monitoring tasks for LDP and LCD could be needed for more appropriate evaluation of the MCR of the RWF.

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