Developing Ergonomic Design Recommendations Using Human-Centric RAMSIS Analysis

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Abstract. This analysis was conducted to determine the utility of the advanced ergonomic analysis tools in the RAMSIS software. Specifically, this report demonstrates how RAMSIS can be effectively used to provide detailed design recommendations which improve operator comfort in an excavator control cabin. A literature review of similar ergonomic investigations in heavy machinery and construction was conducted to provide background information to guide the analysis and context for future work. The ergonomic issues in the cabin design which were analyzed were the steering wheel positioning, armrests, wrist pads, joysticks, seat, floor pedals, touchscreen, and field of view. The step-by-step approach to this analysis was documented to provide a guide for readers to conduct a similar analysis in other applications. Steps for the analysis include creating manikins to represent edge percentiles of operator population, evaluating the comfort ratings of the default control and seating positions, adjusting cabin components translation and rotation to improve comfort, improving touch screen reach and interaction, and evaluating visibility and comfort during control actuation. A table of cabin components, translation, rotation, and nominal position summarizes the key relevant findings. These data provide useful bounds for excavator designers to make more ergonomically beneficial design decisions earlier in the product's development. With little cost, relative to trial-and-error prototyping, RAMSIS can provide useful insights for a human-centric design.

Keywords: Ergonomics · Comfort · Human performance · RAMSIS · Computer-aided design

1 Introduction and Background

1.1 Introduction of RAMSIS

When designing heavy machinery controls, human comfort is often a lesser priority but is a critical consideration when trying to maximize the performance of a human-machine system. Additionally, when these ergonomic factors are addressed, there is often an insufficient range of human body dimensions considered to effectively conform the work environment to each operator [1]. Traditionally, these ergonomic analyses

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are made via inspection of a physical prototype which is costly and prevents rapid design adjustments to arrive at the best solution. This report investigates a method of using computer-aided design of the environment along with ergonomic analysis software (RAMSIS) to generate detailed and actionable design recommendations. The focus is to alleviate awkward joint angles, enhance the field of view, improve the reach of controls, prevent repetitive stress injuries, and create adjustability to fit the operator's dimensions.

RAMSIS is an ergonomic analysis software with embedded tools to create human representative manikins and place them into the human-machine CAD model to quantitatively assess comfort and other ergonomic interactions. The software is an applied example of the concept of digital human modeling (DHM), more commonly referred to as human digital modeling in human factors contexts. The basic premise of DHM is creating a digital representation of a human being and evaluating it in a simulated environment to facilitate the ergonomic assessment of that interaction [2]. In an excerpt from the *Handbook of Human Factors and Ergonomics: Chapter 35*, "For the practicing engineer, human digital modeling represents the opportunity to reduce the need for physical prototyping as it typically makes the analyses available through commercial computer-aided engineering CAE)" [3].

1.2 Background and Literature Review

To provide some guiding background information for this analysis, the initial steps of a systematic literature review were conducted. The purpose of this effort was to reveal current research trends relative to this RAMSIS ergonomic analysis and establish context for future work. The protocol for this search was to begin with keyword searches of "heavy machinery ergonomics" and "construction machinery ergonomics" on multiple research databases (Google Scholar via Harzing's Publish or Perish, SpringerLink, Scopus, and Web of Science). The search date ranges were from 1990 to 2021 and no other filters were applied. The number of relevant articles yielded for each database is summarized in Table 1 below.

Table 1. Search results per database

Keywords searched	Heavy machinery ergonomics	Construction machinery ergonomics
Database	**# of Results**	**# of Results**
Google Scholar (Harzing)	1,000	1,000
SpringerLink	1,399	1,794
Scopus	57	271
Web of Science	31	41

The abstract, author, citation, and reference data were then exported from the databases which support this functionality for further bibliometric analysis and visualization. A word cloud using *maxQDA* software was created using the plain text keywords from each search. This cloud, shown in Fig. 1 emphasizes the most common keywords within the articles from the initial database search. This image provides an initial practical screening tool and helps to highlight more relevant search terms for iterating database searches for more targeted and refined results. The keywords: safety, design, construction, engineering, machinery, and ergonomics are the most common, so those articles which focus on those terms were sorted as most relevant.

Fig. 1. Word cloud from database search results

The export files of the abstract, author, and citation information were also used to generate a co-citation visualization web through *VOSviewer* software. Co-citation analysis displays instances of articles being cited together in another publication which reveals clusters of related research. The co-citation visualization in Fig. 2 shows a clear cluster of co-citation in the red area. Further inspection of these sources reveals a cluster of similar topics relating to ergonomic improvement in construction equipment via operator body sensors detecting vibration and shock as well as deep learning predicting sources of operator injury. The general trend of these articles is a retroactive analysis of existing equipment to determine potential ergonomic pitfalls. This points to a potential area of future work, where pairing the results of studies like these with focused analysis in RAMSIS could eliminate the discovered sources of operator discomfort.

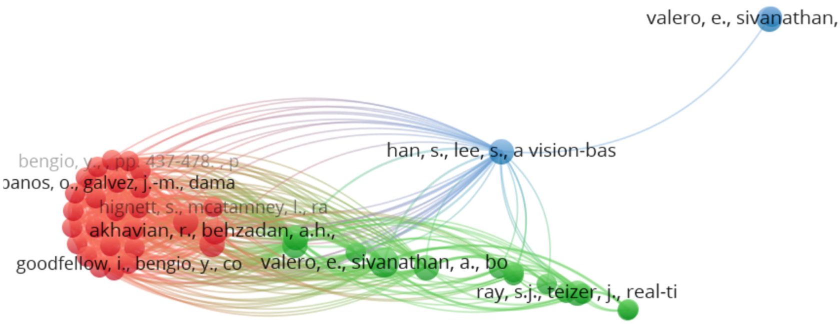

Fig. 2. Co-citation web of search results in scopus

Another method of filtering out relevant research from a large set of database results is to create a pivot chart. This can display top authors, institutions, countries, etcetera which contribute the most to the field of study. Figure 3 shows the most productive authors within the database search for “machinery ergonomics”. This table displays only those authors who produced four or more relevant articles to the keyword search. This provides a useful list to focus the literature review investigation on since the number of publications of an author may indicate their depth of research into that subject.

Fig. 3. Most productive authors within search result field

The trends in existing research show a clear need for improved ergonomic design considerations in heavy machinery over a wide array of industries. For example, operators of pit mining vehicles in the artic are at a high risk of discomfort, musculoskeletal disorders, and occupational accidents due to ergonomic failings in the design of their equipment [4]. Additionally, a study of heavy earthmoving machinery operators which characterized the level of increased exposure to ergonomic hazards such as vibration and poor postural requirements, recommended engineering improved ergonomic controls in the industry [5]. These concerns extend not only to the operation but to the maintenance of these machines, which the operators often need to do themselves in the case of forestry machinery [6]. In all these examples, there is a clear need for improving the ergonomic design considerations in the development of heavy machinery operator environments. The analysis in this report will demonstrate how DHM and the use of RAMSIS and CAD can fulfill this need.

2 Problem Statement

The problem statement leading to this analysis is: can the use of RAMSIS DHM software yield detailed design change recommendations for articulating seating and operator control components in the design of an excavator cabin. Initial work on this topic was documented in *Human-Centric Product Development: Using RAMSIS Ergonomic Analysis to Incorporate Operator Comfort into Excavator Design* [9]. This initial report demonstrated the viability of using RAMSIS to incorporate ergonomic design considerations early on in system development. The following report expands on that analysis in a few areas. It covers a wider percentile of operator body types, and more targeted body positions required for driving, excavator joystick manipulation, and touchscreen interface reach. It also introduces more advanced analysis techniques such as assessing the operator's visual field of view during the various task posture positions.

Similar to the initial analysis, this more in-depth problem is of interest to many industries since this methodology can be applied to any product which encounters ergonomic challenges during its lifecycle due to the human operator being a design afterthought [7]. The methodology for this analysis was based on in-class demonstrations of the software in IE 578 as well as referenced techniques and procedures in the RAMSIS help menu documentation [8]. The following RAMSIS procedures document the steps the authors took to complete this analysis demonstration but are written in a manner to be a helpful, step-by-step instruction flow for readers attempting to replicate the analysis for their learning.

3 Procedure: RAMSIS Ergonomic Analysis of an Excavator

3.1 Creating Boundary Manikins for the Tasks

Reference *Human-Centric Product Development: Using RAMSIS Ergonomic Analysis to Incorporate Operator Comfort into Excavator Design* [9], under the *Procedure* section to set up the RAMSIS software. Multiple manikins are required to assess the ergonomic requirements of a multitude of body shapes and sizes.

The creation of manikins begins with selecting the *Next-Gen Body Builder* tab under the *Start* menu. Select *Anthropometry - > Germany 2004* then *Apply*. Once selected, a manikin will appear with the adjustment settings shown in Fig. 4. Control measurements of *Body Height, Waist Circumference, and Sitting Height* can be adjusted by selecting *Anthropometry - > Typology - > Control Measurements* then selecting *Value,* as seen in Fig. 4 To adjust Dependent Measurements, select *Anthropometry- > Typology - > Dependent Measurements.* Adjust Dependent Measurements by dragging the slider on the left or bottom of the window, while being careful to maintain within the boundary of the blue lines.

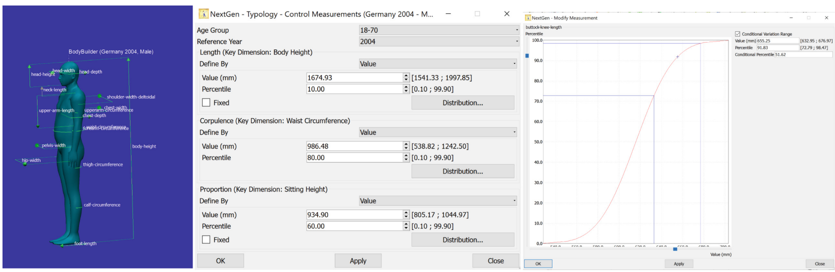

Fig. 4. Manikin control and dependent measurement tabs

Once the values are adjusted, select *Anthropometry - > Add Body Measure List to Structure Tree* to have it selectable for a manikin. Repeat the steps by changing gender and body size to have a wide array of manikins to choose from for ergonomic analysis.

Create a Role for the manikins by selecting the *Role Definition* icon , and creating a Role of *Operator*. Select *PHPT* for the prepositioning point and *Heavy Truck* for the Posture Model as seen in Fig. 5.

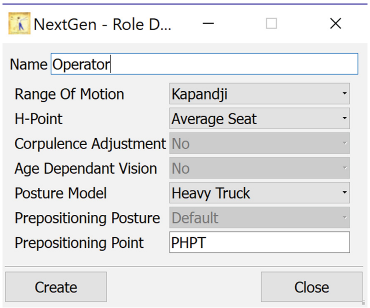

Fig. 5. Operator role defined

Now select the *Test Sample* button , to create multiple manikins with the *Operator Role*. Select *Male/Female* in the *Gender Category* and select the *Body Measure List* radial to select the manikin body measure generated from the previous steps, as seen in Fig. 6. Under the *Role Assignment* tab, select *Operator* and ensure that no shoes are selected under the *Additional Options* tab. Repeat the process to create multiple manikins, ensuring to name them in the Manikin Name section. Reference Fig. 6 to see the variety of manikins included in this analysis. Attach body points by loading the file via *File- > Open* and merging the *.bpt* files included in the RAMSIS setup file. Add work shoes by right-clicking on a manikin, select *Object Properties - > Additional Options,* and select *Work Shoe.*

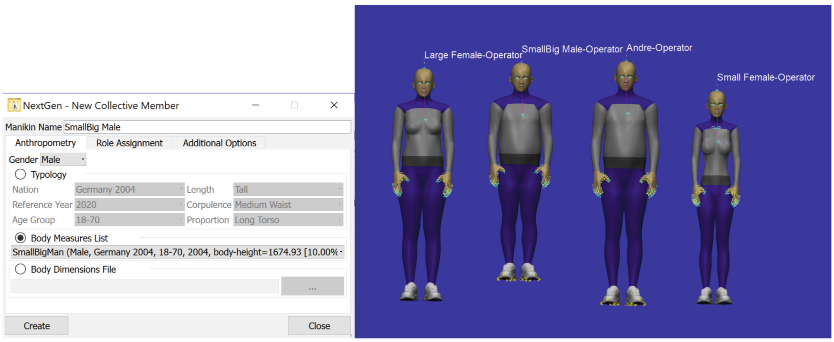

Fig. 6. Manikins of varying sizes and shapes

3.2 Evaluate the Location, Adjustment Range, and Comfort for the Overall Driving Posture

To manipulate the steering wheel components, a *Joint* and *Wheel Point* must be created for rotation and translation of the steering column. First, hide the top components of the steering column to view the base of the steering components. Select *Geometry - > Point - > Create on Object* to create a point on the object in the top right and bottom left as seen in Fig. 7 and Select *Create* for both points. Then change Point Type to *Create Between Points* and select the points for First and Second Points Respectively. Next, create a point on the middle of the steering wheel itself using the same instructions.

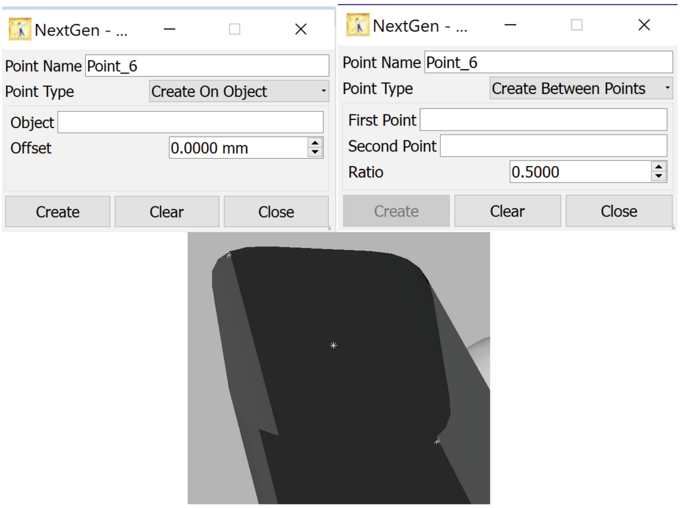

Fig. 7. Creating rotation and translation points

To move the steering group to a nominal ergonomic position, select *Geometry - > Define Kinematics*. When the *Object Kinematics* screen displays, change the name to Steering Wheel. Select the point at the base of the steering column for the *Origin Point.* Add a *Degree of Freedom* of *Rotation* in the Y-axis with a minimum of -30 and a max of 30 degrees. Add the second *Degree of Freedom* of translation between the steering wheel point and steering column points created with a maximum value of 200 mm. Add two objects, first the Steering Wheel itself and then the base of the steering wheel, as depicted in Fig. 8. Click *Create.*

Now that the steering wheel can be manipulated, place the first manikin in the seat to a nominal position. Adjust the steering wheel position by right-clicking on the *Steering Wheel Kinematic,* then select *Object Properties.* In the limits section, increase or decrease the values for rotation and translation. Repeat the manipulations to the steering column position to generate results for nominal position and range.

Nominal positioning for each manakin is determined by iterating adjustment of cabin components and seeing how those changes affect overall manakin comfort. The *Comfort Feeling* and *Joint Capacity* tools are useful ways to quantify the comfort levels of various

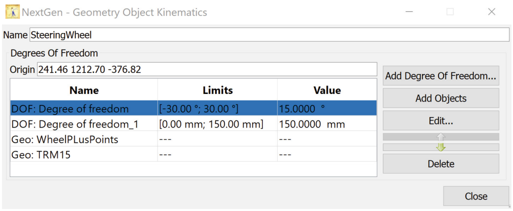

Fig. 8. Define geometry object kinematic input screen

body areas and joints when the manikins are positioned. When using the *Comfort Feeling* Analysis tool as depicted in Fig. 9 set the reference values with no manipulation done to the steering column. Once manipulation is made, select *Posture Calculation* to assess the result of the manipulation to the manikins overall *Comfort.* Continue to manipulate the steering column position until the lowest possible values are achieved and repeat the process for the other manikins. A similar process is done with the *Joint Capacity* tool depicted in Fig. 10, although with this analysis, specific joint discomfort capacity can be used to guide more targeted adjustments. For the steering column and all the following excavator cabin components in this report, these tools were used to derive the nominal position and ranges provided in each section table.

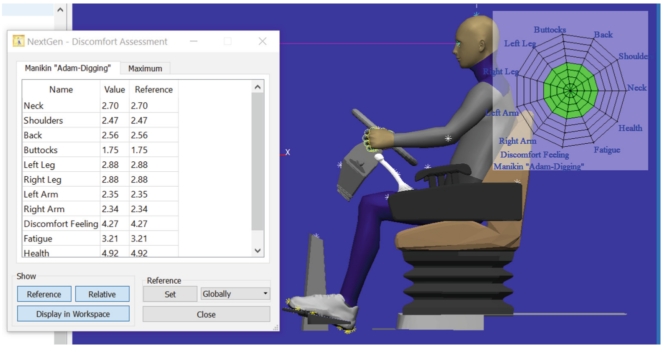

Fig. 9. Using comfort feeling to guide adjustment

After determining nominal steering column positioning using the four manikins, create a rotation of 20 degrees about the Y-axis and a translation of 150mm axially along the steering column. The nominal position of the steering column is depicted in Fig. 11. The range of adjustment to account for the comfort of all the manikins is the adjustability of 5 degrees in rotation and 20mm in translation as seen in Table 2 which displays the optimal position for the individual manikins as well as the range.

3.3 Evaluate the Location, Adjustment Range, and Comfort for Joysticks

To evaluate a range for the joysticks, *Group* the armrests and label them *Armrests.* The joysticks require a translation along the X and Z axes as well as a rotation about the

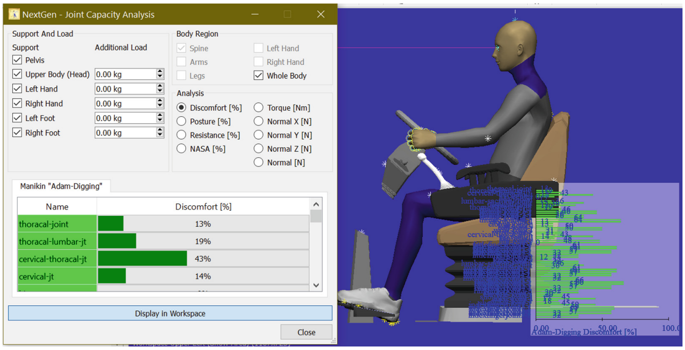

Fig. 10. Using joint capacity to guide analysis

Table 2. Steering column nominal position and range

Steering column	Tall big male	Small big-male	Small female	Large female	Range
Rotation (degrees)	15	20	25	15	20 ± 5
Translation (mm)	150	165	190	170	170 ± 20

Fig. 11. Nominal position of the steering column

Y-Axis to increase the *Comfort Level*. To do so, follow the directions above for *Object Kinematics* and create all three axes for *Degree of Freedom* of *Translational* or *Rotational* respectively with the *Object* as the *Armrest* group created. Ensure the manikin is grasping the joysticks on the left and right. Adjust the armrests for each manakin to decrease the *Discomfort Feeling*. As a technique adjust the manikin to aneutral posture to assess the most relaxed position to attempt to achieve.

The differences between the manikins were more pronounced with the joysticks due to the massive differential in size between the manikins. Table 3 shows the delta between four and shows the range for Rotation (Y-Axis), Translation (X-Axis), and Translation

Z-Axis. Reference Fig. 12 to visualize the results of the range described in Table 3 and the different body positions required without the ability to adjust the armrests.

Table 3. Joystick nominal position and range

Joystick armrests	Tall big male	Small big-male	Small female	Large female	Range
Rotation Y-Axis (degrees)	15	10	5	12	10 ± 5
Translation X-Axis (mm)	0	10	50	20	20 ± 30
Translation Z-Axis (mm)	−40	−50	−60	−50	-50 ± 10

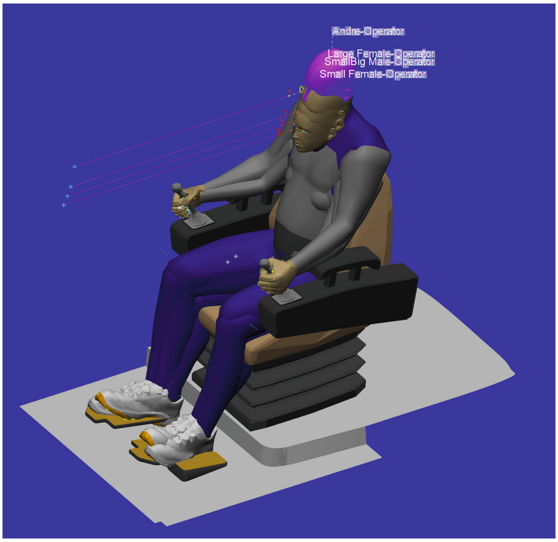

Fig. 12. Nominal position of the joysticks

3.4 Evaluate the Location, Adjustment Range, and Comfort of Wrist Pads

To evaluate a range for the wrist pads, start by performing similar grouping steps and degree of freedom generation as described in Sect. 3.3 but only select the wrist pads and wrist pad supports for grouping. Only a single axis of movement needs to be generated which is parallel with the top of the armrest. This axis will allow the wrist pads to slide forward and aft along the armrest while maintaining their connection regardless of armrest Y-axis rotation. Adjust the wrist pad fore-aft position along the armrests for each manakin to decrease the *Discomfort Feeling* following the same steps as outlined for the armrests.

In the case of the different manikins, the nominal wrist pad range was limited in variability. This is expected because when different body types are gripping the joysticks, their wrists naturally rest in a smaller area towards the front of the armrests. Table 4 shows the delta between the four body types and shows the range for translation along the armrest parallel axis (with negative values being closer to the joystick). Reference Fig. 13 to visualize the results of the range described in Table 4 and the different body positions required to rest the manikin forearm on the wrist pads.

Table 4. Wrist pad nominal fore-aft position and range

Wrist pad position	Tall big male	Small big-male	Small female	Large female	Range
Translation Armrest-Axis (mm)	−15	−20	−25	−15	−25 ± 15

Fig. 13. Nominal position of the wrist pads

3.5 Evaluate the Location, Reach, and Comfort to Touch Screen

To assess the original location of the touchscreen, *Hide/Show* components to have the Touchscreen in view. Define a restriction to reach out and touch the touchscreen via the *Define Restriction* button . Choose the *indexfingertip-r* for the manikin component

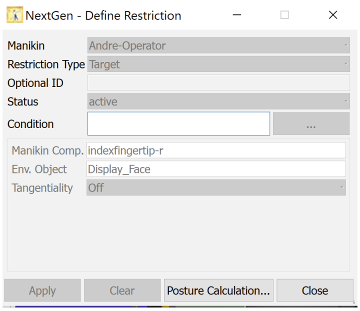

Fig. 14. Defined restriction for touchscreen

and choose the *Display Face* for the environment object as seen in Fig. 14. Ensure to change the line of vision to be looking at the Touchscreen.

Select *Analysis - > Compute Reachability - > Arm right*. Notice in Fig. 15 that all the manikins can reach the top of the touchscreen but are unable to reach the bottom. It is also apparent that the posture required to simultaneously operate the left control and touch the touchscreen is uncomfortable.

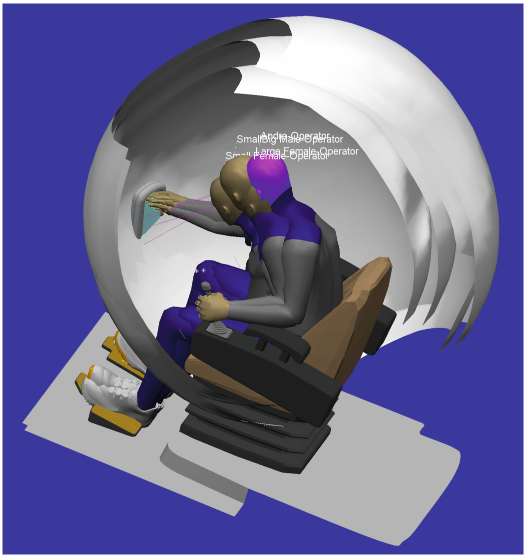

Fig. 15. Manikins unable to reach the bottom of touchscreen.

The touchscreen needs to be moved along the X-axis and the Z-axis to be in reach for the manikins. Define a kinematic with the touchscreen as the object and the degree of freedom as translational in both the X and Z axes. Reference Table 5 to see the ranges of movement required for each manikin to maximize *Comfort Feeling*. The ideal location for the touchscreen is a movement of 120mm and 190mm in the X and Z axes respectively.

Reference Fig. 16 to visualize the final touchscreen location with reachability range included.

Table 5. Touchscreen nominal position and range

Touch screen	Tall big male	Small big-male	Small female	Large female	Range
Translation X-Axis (mm)	100	120	140	120	120 ± 20
Translation Z-Axis (mm)	200	190	180	190	190 ± 10

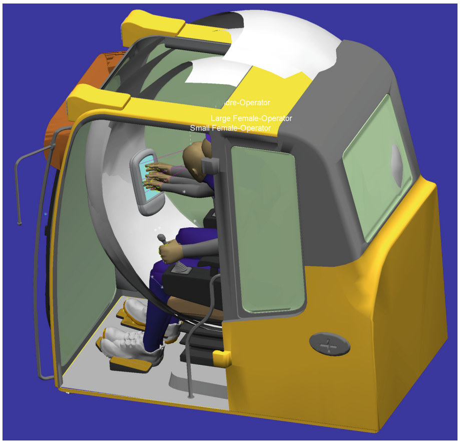

Fig. 16. Final touchscreen location inside reachability range

3.6 Evaluate Visibility and Comfort While Actuating Controls

To assess whether the changes made to the locations of components of the excavator affect the visibility while actuating the controls, first create a point on the display screen using the *Geometry* - > *Point* tool. Select *Operations* - > *Move Eye* to adjust the settings of where the manikin is looking. Select the *Viewing Task* to *Lok at Object,* the *Geometry Point* to the point created on the touch screen, and *Move Starting with* to *Neck.* Checkmark *Consider Posture Model* as seen in Fig. 17 and select *Apply.*

Now that the manikin is looking at the touchscreen, bring back the steering wheel components via *Hide/Show.* Select *Analysis* - > *Vision* - > *Internal View* to view the visibility from the manikin's perspective. Repeat the process with the manakin operating both controls and reaching to manipulate the touch screen while operating the left control. Finally, repeat the process with the varying-sized manikins to assess their sightlines. Figure 18 shows that in both positions, the changes made to the locations of the controls and touch screen give the manikins a clear sightline to the touch screen itself.

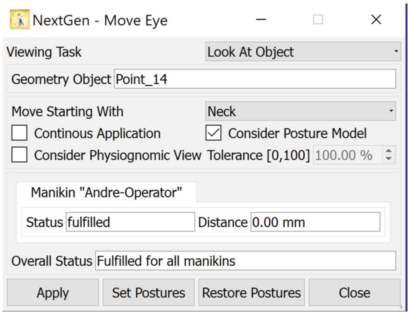

Fig. 17. Move eye input parameters

3.7 Recommended Design Changes

The recommended range of adjustments for each component of the cabin that interfaces with the operator are summarized in Table 6. These adjustment ranges support the ergonomic development of the excavator which will be adaptable to manikin ranges from the 5th-95th percentile of human body type based on the RAMSIS demographic records used. This approach of using RAMSIS to incorporate DHM, allows engineers to start from confidently derived nominal ergonomic design ranges to develop the adjustment mechanisms which conform to operator comfort instead of forcing operators to fit into uncomfortable environments. This is not to imply that design tradeoffs and limitations of cost, materials, schedule, etc. won't still exist, but the process can now fully incorporate ergonomic variables into those decisions.

In addition to supporting better human-centric design, RAMSIS analysis has the added benefit of generating these design parameters without requiring the time and cost-intensive construction of a full-scale prototype. While a prototype may still be prudent to test operator interaction, rapid iterations in the design to improve ergonomics can be done with RAMSIS comfort analysis tools before any physical prototype is built. In the case of this analysis, there are clear changes that need to be made in the steering column, joystick/wrist pad orientation, and position of the touch screen to support operator comfort and visibility to prevent unnecessary fatigue and repetitive stress injuries.

4 Discussion

Both authors have experience as Air Force pilots being in the operator role of a human-machine system and having to compensate because of poor ergonomic decisions in cockpit design. In many cases, these drawbacks in ergonomics are not just an impediment to comfort and a source of repetitive stress injury, but significantly impact the maximum capable human performance that can be expected of the operator. Even though humans are excellent at adapting to challenging situations, any level of pilot compensation required due to poor ergonomics still taxes the finite resources of human processing power and can therefore hinder tactical execution. Often, these poor ergonomic decisions are not a necessary tradeoff for the priority of aircraft performance but simply an oversight or lack of considering operator comfort during early design and prototyping.

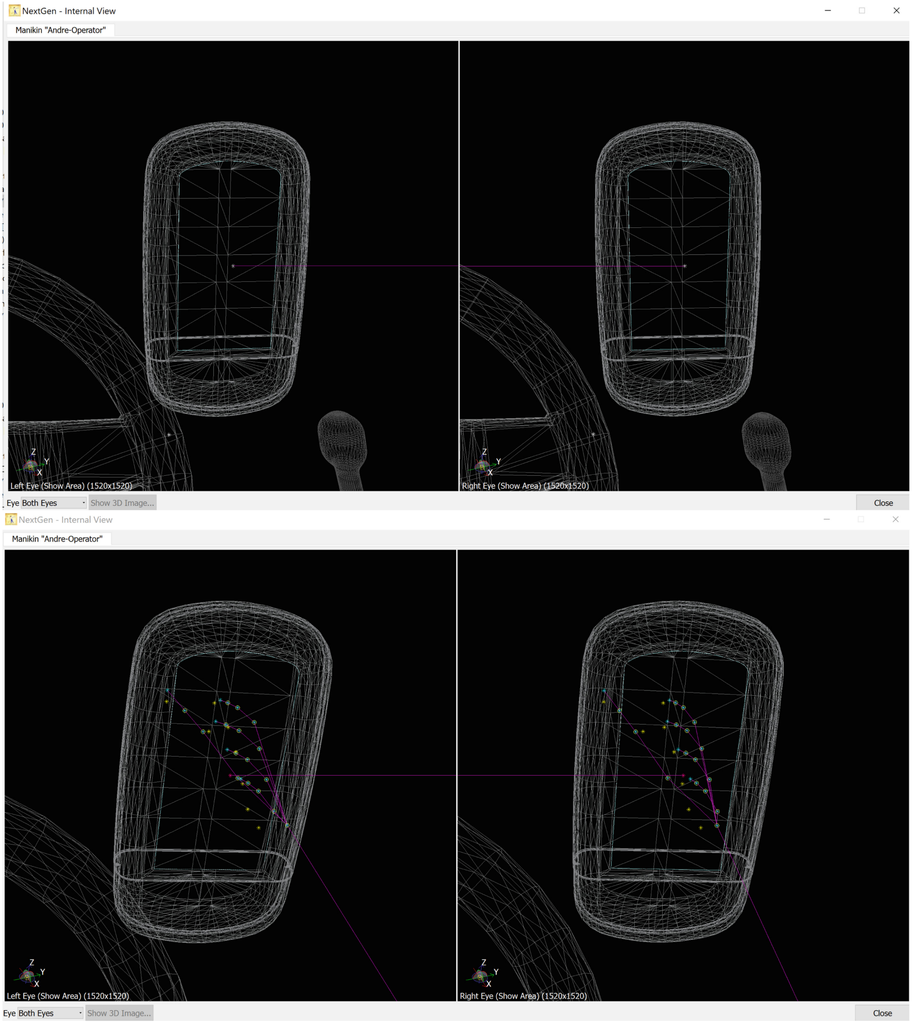

Fig. 18. Clear sight lines to touch screen panel (Top: operating both joysticks, bottom: operating left joystick and reaching for touch screen)

When contractors bring in pilots to assess ergonomics it is often well into the prototype stage where major cockpit configuration changes can be schedule and cost-prohibitive. An alternative approach could be to introduce DHM tools during very early cockpit design mockups in CAD to make those changes while the design is still fluid.

A challenge we faced during this analysis was encountering posture calculations which resulted in the manikin "clipping" with components of the seat. Specifically, armrest adjustments were forcing the manikin to lean back through the physical structure of the seatback. This can be prevented by creating a restriction from the skin point on the manikin's back to a geometry point on the chair, effectively pinning the manikin to

Table 6. Summary of comfort adjustment ranges

Steering column	Tall big male	Small big-male	Small female	Large female	Range
Rotation (degrees)	15	20	25	15	20 ± 5
Translation (mm)	150	165	190	170	170 ± 20
Joystick Armrests					
Rotation Y-Axis (degrees)	15	10	5	12	10 ± 5
Translation X-Axis (mm)	0	10	50	20	20 ± 30
Translation Z-Axis (mm)	−40	−50	−60	−50	−50 ± 10
Touch Screen					
Translation X-Axis (mm)	100	120	140	120	120 ± 20
Translation Z-Axis (mm)	200	190	180	190	190 ± 10
Wrist Pad Position					
Translation Armrest-Axis (mm)	−15	−20	−25	−15	−25 ± 15

the chair back. If there is an easier way to address this such as a setting that prohibits manikin clipping, that would be useful information to present future students.

5 Future Work

The capability of RAMSIS to aid designers in evaluating many details of operator comfort has been demonstrated. Specific translation and rotation ranges of cabin components provide a clear operating envelope for engineers to design adjustment mechanisms to suit operators of different sizes. However, these investigations were all conducted in a static environment within the RAMSIS software. Heavy machinery like an excavator will introduce abrupt movements and steady vibrations to the operator regardless of the positioning of their joints and reach. Future investigation into the excavator should address dynamic ergonomic considerations such as vibration, shear load, impact, sound, etcetera, and how those could negatively affect operator performance and health. Ways to address these dynamic issues could include seat bolstering, seatbelts or straps, and pliable seat material like foam or large spring dampers. The adjustments determined in RAMSIS to support nominal posture are a solid foundation but are just the starting point to develop an operator environment that will promote maximum human performance and support long-term health.

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