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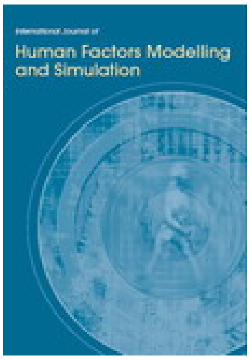

International Journal of Human Factors Modelling and Simulation

ISSN online: 1742-5557 - ISSN print: 1742-5549
https://www.inderscience.com/ijhfms

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DOI: 10.1504/IJHFMS.2024.10068501

Article History:

Received:	04 June 2024
Last revised:	14 August 2024
Accepted:	28 August 2024
Published online:	06 January 2025

Use of JACK modelling software to quantify the reachability of ISO 6682

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Abstract: For decades, human factor experts have pushed for the redesign of mining machine cabs to improve operator sightlines and ergonomics. Current cab design does not accommodate a full range of operator sizes, causing many workers to adopt non-neutral postures, which can increase their risk for musculoskeletal injury. This work examined the reachability of the zone of comfort (ZoC) for hand control locations in JACK software as defined for a range of operators. Once reach envelopes were overlaid onto the cabs for a variety of sized operators, no condition existed where an operator could reach 100% of the ZoC for hand controls. The best reachability was achieved by the largest operator, while the 5th percentile Latino female can fully reach only 29.7% of controls without using flexion. This work is the first to examine the validity of ISO 6682 from an equity, diversity, and inclusion perspective.

Keywords: equity; diversity; inclusion; classic JACK modelling; anthropometric mismatch; reachability; reach envelope; International Organization for Standardization; ISO; mining cab design; mining industry; ISO 6682; zone of comfort; ZoC.

Reference to this paper should be made as follows: Perfetto, S., Goggins, K., Cloutier, M. and Godwin, A. (2024) 'Use of JACK modelling software to quantify the reachability of ISO 6682', *Int. J. Human Factors Modelling and Simulation*, Vol. 8, No. 5, pp.1–20.

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1 Introduction

Research has indicated that there has been a need to redesign the cabs of earth-moving machinery for decades (Bátiz-Flores et al., 2021; de Looze et al., 2000; Godwin et al., 2010; Mejia et al., 2010; Sen et al., 2020). The major goal of a redesign would be to improve operator sightlines, while also reducing the frequency of awkward postures being used during machine operation. Redesign suggestions include maintaining the placement of controls across similar types of equipment (Unger, 1996), minimising cab post profiles (Godwin et al., 2008), incorporating swivelling seats (Bottoms and Barber, 1978), and minimising the degree of wrist movement required to operate controls (Oliver et al., 2000). However, cab design, design suggestions, and design standards are rarely examined from an equity, diversity, and inclusion (EDI) perspective, which more wholly considers the needs of a range of operators representing different ethnicities and anthropometrics. Embedding EDI into design strategies early in the process helps to further address inequitable safety outcomes, and ultimately achieve safety equity for a diverse workforce.

The International Organization for Standardization (ISO) is responsible for the development of standards related to technology, testing procedures, working conditions, and more. The ISO has published a number of standards relating to earth-moving machinery and workplace conditions, many of which can be applied to the mining industry to maintain employee health and safety. For instance, ISO 6682 (1986) outlines the comfort zone for the location of controls within earth-moving machinery. It is intended to be used by machine manufacturers in the design of cab control layouts to ensure that the control placement allows most individuals to operate the machines comfortably. ISO 6682 (1986) provides coordinates that define two zones of controls: the zone of comfort (ZoC), and the zone of reach. The ZoC defines the preferred location for primary controls, or controls used frequently by the operator, such as brakes, steering, and speed controls. According to ISO 6682 (1986), controls within the ZoC should be accessible to the operator without any trunk abduction. The zone of reach defines the location of secondary controls, or controls used infrequently by the operator, such as lights, starters, and temperature controls. ISO 6682 (1986) states that small and large operators should be able to access the secondary controls while in a seated position but may need to rotate or flex the trunk.

The coordinates outlined in ISO 6682 (1986) are based on both male and female anthropometrics from the USA, Europe, and Asia. Anthropometrics influence how an individual can interact with equipment controls (Strasser, 1995), with the smallest individuals representing the limiting factor for the size of the maximum reachable area for operators (Sengupta and Das, 2000). Thus, the smallest potential operators must be considered in workstation design. Additionally, in 2016, indigenous individuals comprised 12% of the Canadian upstream mining workforce; however, the current data used to develop standards related to earth-moving machinery, do not include anthropometrics for indigenous or Latinx individuals.

The benefits of increasing EDI within a company are very well documented, and include: the promotion of trust and employee engagement (Machin and Jeffries, 2013); the generation of a sense of fairness, belongingness, uniqueness; and promotion of workplace innovation due to the diverse climate/culture among employees (Jones et al., 2021). Improving EDI also results in increased cultural competency and cultural humility within the workplace (Nair and Vohra, 2015), as well as increased job satisfaction (Downey et al., 2015), patient/client satisfaction, sales revenue, number of customers, market share, relative profits (Herring, 2009), and improved overall workplace outcomes (Francis et al., 2022).

Equity relates to the recognition and elimination of barriers to provide individuals with different levels of support, ensuring that all individuals have fair and equal access to opportunities and resources (Baum, 2021). Diversity relates to the mix of representation within a workforce, and relates to gender diversity, ethnic diversity, age diversity, physical ability, etc. (Nair and Vohra, 2015). Inclusion is the degree to which individuals of all social identity groups have the opportunity to be present, heard, appreciated, and engaged in workplace activities, contributing to a sense of belongingness (Nair and Vohra, 2015). Given the benefits, workplaces are making a more concerted effort to improve their EDI, however, the influence of increased EDI on the range of workforce anthropometrics is often not considered. The collection of up-to-date anthropometric data, including a diverse range of body sizes, shapes, and proportions, should be considered to enhance diversity in design and inclusion (Wooldridge et al., 2022).

Non-inclusive vehicle design that fails to consider EDI, and does not fit a range of anthropometrics, not only increases the risk of fatigue and musculoskeletal disorders (MSDs) (Keyserling et al., 1988; Mejia et al., 2010), it is also one of the main causes of mining equipment accidents (Dhillon, 2009). Cabs that are not designed for the anthropometrics of a wide range of users can result in the adoption of non-neutral working postures, and these postures are linked to an increased risk of MSDs (Charles et al., 2018; Eger et al., 2008; Heine et al., 2020; Keyserling et al., 1988; Schutte and Shaba, 2003; Brkić et al., 2023; Zimmermann et al., 1997). MSDs may present as lower back pain, neck discomfort, and shoulder discomfort, which are all commonly reported amongst workers in the mining industry (Brkić et al., 2023; Sen et al., 2020). Some workers may be disproportionately presented with inequitable safety outcomes such as MSDs, which highlights the importance of equipment design that considers how all individuals interact with a system (Stonewall et al., 2021). Specifically, part of EDI is considering age, sex, gender, physical differences, and cultural differences during the early design process. In addition to MSD risk, existing cab designs can have reduced sightlines (Godwin et al., 2010; Heine et al., 2020) and inaccessible emergency controls, which are linked to increased accident risk (Dhillon, 2009; Eger et al., 2004).

No existing work has validated the placement of the ISO 6682 (1986) coordinates relative to mining equipment cabs, or considered the reach envelopes of potential operators in the mining industry. Accordingly, this study highlights the limitations in accessibility of the ZoC defined in ISO 6682 (1986) within earth-moving mining machinery. This study had three objectives:

1 examine the locations of the coordinates for the ZoC relative to the cabs of four different-sized mining machines

2 compare the locations of the coordinates for the ZoC to the simulated reach envelope of five standardised, digital manikins

3 overlay the reach envelopes into each of the cabs to display the accessibility limitations of the ZoC relative to cab design and user anthropometrics.

2 Methods

2.1 Cab design

JACK software (version 9.0, Siemens Industrial Software Company) was used to model the cabs of four different mining machines as well as five digital manikins. AutoCAD models of the machines were reverse engineered from pictures and imported as VRML files into Classic JACK. The cabs of a select four machines used and these included two front-facing dump trucks (FFDT1 and FFDT2), and two side-facing load haul dump trucks (SFLHT1 and SFLHT2). A typical mining seat was imported from the JACK library placed within the cabs in accordance with measure R3 in ISO 3411 (2007).

2.2 Coordinates, manikin properties, and placements

ISO 6682 (1986) defines 24 coordinates that outline the ZoC for the location of hand controls. The 12 coordinates chosen for this study are listed in Table 1 and these were generated as points in JACK and placed in relation to a seat index point (SIP) at coordinate (0, 0, 0) (ISO 6682, 1986).

For this study, coordinates were placed on both the left (‘l’) and right (‘r’) sides of the manikin. Five manikins were used in these analyses: small (5th percentile), medium (50th percentile), and large (95th percentile) manikins based on North American operators, as shown in Figure 1 and outlined in ISO 3411 (2007); as well as manikins scaled to represent 5th percentile indigenous (Katzmarzyk and Malina, 1999) and Latino females shown highlighted in red in Figure 1 (Siemens Tecnomatix JACK, 1993–1999).

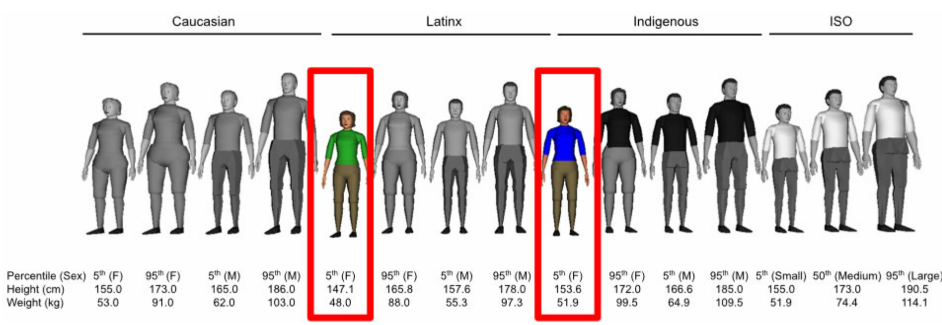
Manikins were loaded into a default seated position for analysis. Manikins were moved by their hip-point (H-point) to be placed in a standardised location relative to the SIP according to ISO 5353 (1995). The H-point of an operator is typically 0.5 cm to the fore of the SIP, and there is no significant vertical difference between the H-point and the

SIP (Reed and Ebert, 2014). The seats were modelled with 15 cm of fore-aft adjustment and 7.5 cm of vertical adjustment, in accordance with ISO 6682 (1986). As per ergonomic recommendations in ISO 6682 (1986): for the 5th percentile operators, the seat was adjusted to the highest and foremost setting; for the 95th percentile operator, the seat was adjusted to the lowest and rearmost position; and for the 50th percentile operator, the seat was set to its centremost position.

Table 1 Coordinates as defined in ISO 6682 (1986) – Annex B, Table 2 coordinates for zone of comfort – hand control location zone

Point label	*Coordinates (X, Y, Z)*
A_1	(132, 500, 425)
A_2	(132, 500, –100)
B_1	(132, 400, 425)
B_2	(132, 400, –100)
C_1	(230, 250, 425)
C_2	(230, 250, –100)
D_1	(296, 250, 425)
D_2	(296, 250, –100)
E_1	(530, 500, 425)
E_2	(221, 500, –100)
F_1	(573, 400, 425)
F_2	(296, 400, –100)

Figure 1 The anthropometric data (i.e., height and weight) of Caucasian, Latinx, and indigenous individuals in contrast to the anthropometrics used in ISO standards



Source: International Organization for Standardization (2007), Katzmarzyk and Malina (1999) and Siemens Tecnomatix JACK (1993–1999, 1997)

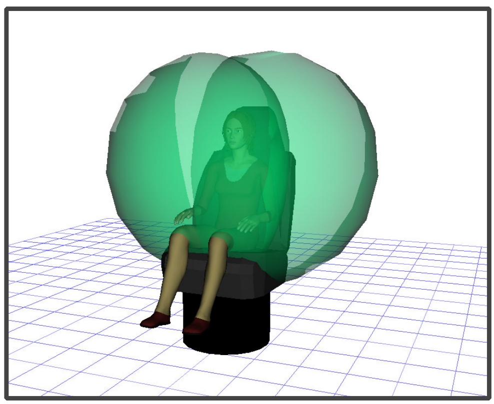
2.3 Coordinate location in relation to cabs

The first analysis determined where the coordinates defining the ZoC were located in relation to each of the four cabs. The coordinates for the ZoC outlined in ISO 6682 (1986) were superimposed on the cab files within the JACK environment. The coordinates were colour coded based on their observed location relative to the interior of the cab. Coordinates that were inside of the cab were coloured green, coordinates that were partially inside of the cab were coloured orange, and coordinates that were outside of the cab, and thus inaccessible from the inside of the cab, were coloured red. The percentages of coordinates fully inside, partially inside, and fully outside of the cab were calculated for each machine.

Table 2 The coordinates of each manikin's H-point placement based on respective seat adjustments

Manikin percentile	*H-point coordinates*
95th	(–7.0, –3.75, 0.0)
50th	(0.5, 0.0, 0.0)
5th	(8.0, 0.0, 0.0)

Figure 2 Visualisation of the primary reach zones (e.g., green bubbles) generated in JACK software for the right and left fingertip location of an example manikin in 0-degree hip flexion with back against the seat (see online version for colours)



2.4 *Coordinate location in relation to operators*

The second analysis examined the location of the ISO 6682 (1986) coordinates relative to the reach envelopes of the five operators. The coordinates were placed relative to the SIP coordinates (0, 0, 0) while the operators were placed by the H-point at the coordinates listed in Table 2 to be representative of the respective seat adjustment in the cab. The reach envelope for each operator was created through the reach zones tool on JACK as depicted in Figure 2, which shows the reach zone associated with body movement restricted to the shoulder joint only and no trunk flexion. The second comparison allowed for 20-degree trunk flexion in the forward and lateral directions, which is used as the maximum trunk movement angle in ISO 6682 (1986). The tip of the index finger was used as the trace site for each manikin and is represented by the circular shape shown in Figure 2. The reach envelope was developed using both the right and left hands. The number of coordinates fully within, partially within, and fully outside of the reach envelopes were coloured green, orange, and red, respectively. The percentage of coordinates fully inside, partially inside, and fully outside of the operator's reach envelope was calculated for each operator size with no trunk flexion, and with 20-degree flexion in the forward and lateral directions.

2.5 Coordinate accessibility within cabs for each operator

The third analysis overlaid the simulated operator reach envelopes onto the modelled cabs to provide a realistic overview of the reachability limitations due to both cab design and operator anthropometrics. The requirements for colour classifications of the coordinates are outlined in Table 3. Descriptive statistics are presented as frequencies and percentages due to the categorical nature of the data.

Table 3 Criteria for colour classifications of coordinates used in analysis three

Colour	*Criteria*
Green	• Coordinate fully within cab AND reach envelope
Orange	• Coordinate fully within cab BUT partially within reach envelope
	• Coordinate fully within reach envelope BUT partially within cab
	• Coordinate partially within cab AND reach envelope
Red	• Coordinate fully or partially within cab BUT fully out of reach envelope
	• Coordinate fully or partially within reach envelope BUT fully out of cab
	• Coordinate fully out of cab AND reach envelope

3 Results

3.1 ISO 6682 coordinate location in relation to equipment cabs

The first objective determined the location of the coordinates (n = 24) relative to each of the four cabs. Table 4 uses a 3-colour scheme to highlight whether coordinates fell fully, partially or not at all within the cab. Quantitatively, SFLHT2 had the lowest number of points fully within the cab (41.7%), followed by the FFDT2 (50.0%), FFDT1 (66.7%), and finally, SFLHT1 (75.0%). Before the operator was even incorporated into the simulation, 16.7% (FFDT1 and SFLHT1), 33.3% (FFDT2), and 37.5% (SFLHT2) of the hand control locations, as defined in ISO 6682 (1986), were not even located within the equipment cab. Six of the 24 coordinates (25.0%) were not located within any of the equipment cabs tested in this study (i.e., A_2r, E_2r, A_1l, A_2l, E_1l, and E_2l).

3.2 ISO 6682 coordinate location in relation to simulated operators

The anthropometrics (i.e., height and weight) for each of the populations used as manikins for JACK simulation are displayed in Figure 1. It is evident that the 5th percentile indigenous and Latino females (outlined in red) are smaller than the small operator manikin defined in ISO 6682 (1986). Therefore, these two populations are not represented by the recommended ZoC and reach zone defined in ISO 6682 (1986).

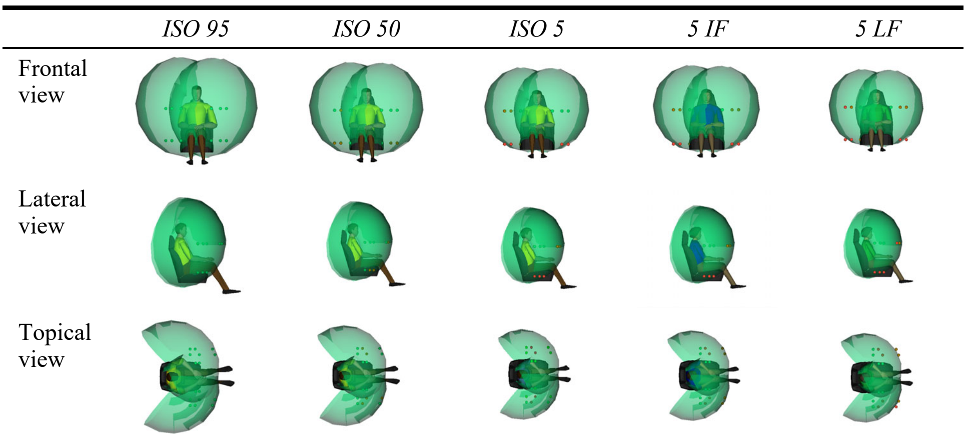
Table 4 The location of coordinates for each of the modelled heavy equipment cabs according to the criteria of colour classification (see online version for colours)

Point	*FFDT1*	*FFDT2*	*SFLHT1*	*SFLHT2*
A_1r				
A_2r				
B_1r				
B_2r				
C_1r				
C_2r				
D_1r				
D_2r				
E_1r				
E_2r				
F_1r				
F_2r				
A_1l				
A_2l				
B_1l				
B_2l				
C_1l				
C_2l				
D_1l				
D_2l				
E_1l				
E_2l				
F_1l				
F_2l				
Points *fully* in cab (%)	66.7	50.0	75.0	41.7
Points *partially* in cab (%)	16.7	16.7	8.3	20.8
Points *not* in cab (%)	16.7	33.3	16.7	37.5

Notes: Green boxes indicate coordinates that are fully within the cab, orange boxes indicate coordinates that are partially within the cab, and red boxes are indicative of points that are outside of the cab.

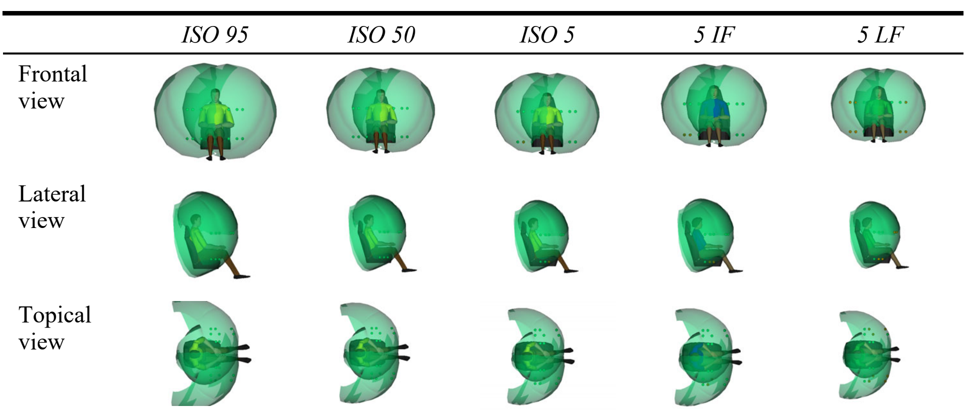
The JACK simulation of the coordinates, and each of the five manikin's reach envelopes were depicted with no trunk flexion in Figure 3, and with 20-degree trunk flexion in the forward and lateral directions in Figure 4. These figures provide the frontal, lateral, and overhead views. It is evident from Figure 3 that without trunk flexion, only the large ISO 3411 (2007) operator (95th percentile) could reach all (i.e., 100%) of the coordinate locations, as supported by the first column of green boxes in Table 5. The medium ISO 3411 (2007) operator (50th percentile) could either fully reach (79.2%) or partially reach (20.8%) all coordinate locations. Meanwhile, the 5th percentile operators could only fully reach between 41.8% (5th percentile Latino female) and 58.3% (small ISO 3411 (2007) operator) coordinate locations. Focusing on the small ISO 3411 (2007) operator and the 5th percentile indigenous female models in Figure 3, it is evident that they could not fully reach five (out of 24) of the coordinates. Furthermore, Table 5 highlights that with no trunk flexion, the 5th percentile Latino female could not fully reach seven (out of 24) of the coordinates.

Figure 3 Visual display of the ISO 6682 (1986) Table 2 coordinates for zone of comfort - Hand control location zones in relation to each manikin's reach envelope with no trunk flexion (see online version for colours)



Notes: ISO 95 – large ISO operator (95th percentile); ISO 50 = medium ISO operator (50th percentile); ISO 5 = small ISO operator (5th percentile); 5 IF = 5th percentile indigenous female; 5 LF = 5th percentile Latino female.

Figure 4 Visual display of the ISO 6682 (1986) Table 2 coordinates for zone of comfort - Hand control location zones in relation to each manikin's reach envelope with 20-degree trunk flexion (see online version for colours)



Notes: ISO 95 – large ISO operator (95th percentile); ISO 50 – Medium ISO operator (50th percentile); ISO 5 – Small ISO operator (5th percentile); 5 IF – 5th percentile indigenous female; 5 LF – 5th percentile Latino female.

Once the manikins were able to flex their trunk 20-degrees in the forward and lateral directions, the medium ISO 3411 (2007) operator (50th percentile) could fully reach all (i.e., 100%) of the coordinate locations as shown by the green columns in the second half of Table 5. Figure 4 presents a visual to show how this postural adjustment allowed all of the 5th percentile manikins to fully or partially reach more coordinate locations. Correspondingly, there are no red blocks at all in the second half of Table 5 where results for 20-degrees of flexion were reported.

Table 5 Location of coordinates relative to each manikin's reach envelope (see online version for colours)

Point	*No trunk flexion*					*20-degree trunk flexion*				
	ISO 95	*ISO 50*	*ISO 5*	*5 IF*	*5 LF*	*ISO 95*	*ISO 50*	*ISO 5*	*5 IF*	*5 LF*
A_1r										
A_2r										
B_1r										
B_2r										
C_1r										
C_2r										
D_1r										
D_2r										
E_1r										
E_2r										
F_1r										
F_2r										
A_1l										
A_2l										
B_1l										
B_2l										
C_1l										
C_2l										
D_1l										
D_2l										
E_1l										
E_2l										
F_1l										
F_2l										
Points *fully* in reach envelope (%)	100	79.2	58.3	50.0	41.8	100	100	95.8	91.7	70.8
Points *partially* in reach envelope (%)	0.0	20.8	20.8	29.2	29.2	0.0	0.0	4.2	8.3	29.2
Points *not* in reach envelope (%)	0.0	0.0	20.8	20.8	29.2	0.0	0.0	0.0	0.0	0.0

Notes: Green boxes indicate coordinates that are fully within the reach envelope, orange boxes indicate coordinates that are partially within the reach envelope, and red boxes are indicative of points that are outside of the reach envelope. ISO 95 – large ISO 3411 (2007) operator (95th percentile); ISO 50 – medium ISO 3411 (2007) operator (50th percentile); ISO 5 – Small ISO 3411 (2007) operator (5th percentile); 5 IF – 5th percentile indigenous female; 5 LF – 5th percentile Latino female.

Table 6 Combination of equipment cab and operator reach limitations using the critical coordinates with the manikins in the no trunk flexion position according to the criteria of colour classification defined in Table 3 (see online version for colours)

Point	*FFDT1*					*FFDT2*					*SFLHT1*					*SFLHT2*				
	ISO 95	*ISO 50*	*ISO 5*	*5 IF*	*5 LF*	*ISO 95*	*ISO 50*	*ISO 5*	*5 IF*	*5 LF*	*ISO 95*	*ISO 50*	*ISO 5*	*5 IF*	*5 LF*	*ISO 95*	*ISO 50*	*ISO 5*	*5 IF*	*5 LF*
A_1r																				
A_2r																				
B_1r																				
B_2r																				
C_1r																				
C_2r																				
D_1r																				
D_2r																				
E_1r																				
E_2r																				
F_1r																				
F_2r																				
A_1l																				
A_2l																				
B_1l																				
B_2l																				
C_1l																				
C_2l																				
D_1l																				
D_2l																				
E_1l																				
E_2l																				
F_1l																				
F_2l																				
Points *fully* in cab (%)	66.7	54.2	45.8	41.7	33.3	50.0	45.8	37.5	33.3	29.2	75.0	62.5	50.0	45.8	37.5	41.7	41.7	33.3	33.3	33.3
Points *partially* in cab (%)	16.7	29.2	20.8	25.0	29.2	16.7	20.8	20.8	25.0	29.2	8.3	20.8	16.7	20.8	25.0	20.8	20.8	20.8	20.8	20.8
Points *not* in cab (%)	16.7	16.7	33.3	33.3	37.5	33.3	33.3	41.7	41.7	41.7	26.7	16.7	33.3	33.3	37.5	37.5	37.5	45.8	45.8	45.8

Notes: ISO 95 – large ISO operator (95th percentile); ISO 50 – medium ISO operator (50th percentile); ISO 5 – small ISO operator (5th percentile); 5 IF – 5th percentile indigenous female; 5 LF – 5th percentile Latino female.

Table 7 Combination of equipment cab and operator reach limitations using the critical coordinates with the manikins in 20-degree trunk flexion in the forward and lateral directions according to the criteria of colour classification defined in Table 3 (see online version for colours)

Point	*FFDT1*					*FFDT2*					*SFLHT1*					*SFLHT2*				
	ISO 95	*ISO 50*	*ISO 5*	*5 IF*	*5 LF*	*ISO 95*	*ISO 50*	*ISO 5*	*5 IF*	*5 LF*	*ISO 95*	*ISO 50*	*ISO 5*	*5 IF*	*5 LF*	*ISO 95*	*ISO 50*	*ISO 5*	*5 IF*	*5 LF*
A_1r																				
A_2r																				
B_1r																				
B_2r																				
C_1r																				
C_2r																				
D_1r																				
D_2r																				
E_1r																				
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C_2l																				
D_1l																				
D_2l																				
E_1l																				
E_2l																				
F_1l																				
F_2l																				
Points *fully* in cab (%)	66.7	66.7	62.5	62.5	54.2	50.0	50.0	50.0	50.0	45.8	75.0	75.0	70.8	70.8	58.3	41.7	41.7	41.7	41.7	41.7
Points *partially* in cab (%)	16.7	16.7	20.8	20.8	29.2	16.7	16.7	16.7	16.7	20.8	8.3	8.3	12.5	12.5	25.0	20.8	20.8	20.8	20.8	20.8
Points *not* in cab (%)	16.7	16.7	16.7	16.7	16.7	33.3	33.3	33.3	33.3	33.3	16.7	16.7	16.7	16.7	16.7	37.5	37.5	37.5	37.5	37.5

Notes: ISO 95 – large ISO operator (95th percentile); ISO 50 – medium ISO operator (50th percentile); ISO 5 – small ISO operator (5th percentile); 5 IF – 5th percentile indigenous female; 5 LF – 5th percentile Latino female.

3.3 ISO 6682 coordinate accessibility within equipment cabs for each simulated operator

Finally, the four machine cabs and five operator reach envelopes were combined for simulation. Tables 6 and 7 demonstrate the resulting reachability of the critical coordinates without trunk flexion (Table 6) and with 20-degree trunk flexion in the forward and lateral directions (Table 7). Regardless of the equipment type, manikin size, and trunk position, four coordinates (A_1l, A_2l, E_1l, and E_2l) on the left-hand side were never reachable as observed by the four completely red rows in Table 6. Hence, none of the conditions used in this study allow the operators to reach 100% of the possible coordinate locations as outlined in ISO 6682 (1986).

Without trunk flexion, the large ISO 3411 (2007) operator (95th percentile) could reach a maximum of 75.0% (SFLHT1) and a minimum of 41.7% (SFLHT2) of the coordinates. The medium ISO 3411 (2007) operator (50th percentile) could reach a maximum of 62.5% (SFLHT1) and a minimum of 41.7% (SFLHT2) of the coordinates. The small ISO 3411 (2007) operator (5th percentile) could only reach a maximum of 50.0% (SFLHT1) and a minimum of 33.3% (SFLHT2) of the coordinates. The reachability got progressively worse for the 5th percentile indigenous female operator (a maximum of 45.8% for the SFLHT1 and a minimum of 33.3% for SFLHT2 and FFDT2), and the 5th percentile Latino female operator (a maximum of 37.5% for the SFLHT1 and a minimum of 29.2% for the FFDT2).

Interestingly, the coloured blocks and corresponding values in Table 7 demonstrated that when using 20-degrees of trunk flexion in the forward and lateral direction, the minimum reachability became universal at 41.7% in the SFLHT2 regardless of the operator size. The maximum reachability of the control locations occurred in the SFLHT1 at 75.0% (ISO 3411 (2007) large and medium operators), 70.8% (ISO 3411 (2007) small and 5th percentile indigenous female operators), and 58.3% (5th percentile Latino female operator).

4 Discussion

To start, the ISO 6682 (1986) ZoC coordinates (i.e., the preferred location zones for primary hand and foot controls) were examined using only the cabs of four pieces of mining equipment. The lowest percentage of ISO 6682 coordinates within a cab was 41.7% for the SFLHT2, followed by the FFDT2 (50.0%), FFDT1 (66.7%), and finally, SFLHT1 (75.0%). These findings demonstrate that regardless of operator size, sex, or ethnicity, operators cannot access 58.3% of the ZoC in the SFLHT2, as 14 coordinates are located outside of the cab. Of the 24 possible coordinate locations, without incorporating their reach envelope, operators only had the potential to reach a maximum of 18 coordinate locations. Six points (A_2r, E_2r, A_1l, A_2l, E_1l, and E_2l) were not located within any of the cabs. The implication is that the interiors of the cabs tended to be too small to allow for all of the ZoC coordinates for hand and foot controls to be inside of the cab. Further, the dimensions of the cabs indicate that some controls are not optimally located for human use due to the limits of space and available ZoC coordinates within the cab.

The second part of this study compared the locations of the coordinates to each of the five operators' reach envelopes while considering adjustments in seat positions. Without adopting a flexed, awkward posture, only the large ISO operator can reach 100% of the ZoC coordinates. Meaning, for hand control comfort and reachability, ISO 6682 is only ideal for the 95th percentile operators while maintaining a neutral, seated posture. While ISO 6682 states that the coordinate locations were developed based on both small and large operators, the findings from this study contradict this statement. The medium and small ISO operators only have 79.2% and 58.3% of ISO 6682 coordinates fully within their reach envelopes, respectively, without adopting a flexed posture.

The two manikins that are not represented in the ISO specifications had even poorer accessibility compared to the ISO manikins. Only 50.0% and 41.7% of the controls were fully within the reach envelopes of the 5th percentile indigenous and Latino females, respectively, with no trunk flexion. The reachability increases to 91.7% and 70.8%, respectively, once allowing for 20-degree trunk flexion. In a real-world scenario, even with bending at the trunk to reach controls and risking MSDs, these two operators still could not reach the entire ZoC. Thus, it is clear that the 5th percentile indigenous and Latino female operators are not considered in cab design, as the ISO anthropometrics used in design standards do not accommodate their anthropometrics, despite making up a fair proportion of the Canadian mining population (Statistics Canada, 2023). This finding raises concerns as the anthropometrics being used for design purposes are not an actual representation of the workforce, thus creating a lack of accessibility and inclusion. More specifically, accessibility is an essential component of both equity and inclusion, and if controls are inaccessible to indigenous and Latino female operators, these workers cannot complete their tasks in an efficient manner (Stonewall et al., 2021), and are less likely to be hired into these positions. The lack of accessibility creates barriers and demonstrates that EDI is often overlooked in the design and engineering process (Stonewall et al., 2021). Addressing the exclusion of indigenous and Latino female operators in cab design, especially in the context of Canadian mining, requires universal and accessible designs that incorporate a safety equity lens (Stonewall et al., 2021). Taking the time to incorporate these two populations into the ISO specifications is vital, and can be done by partnering and collaborating with EDI groups to specifically focus on the anthropometrics of indigenous and Latino female operators. Additionally, efforts need to be made to adjust the ISO standards to improve inclusion for operators of all sizes.

Table 4 displays the ISO 6682 areas that are most commonly outside an operator's reach envelope. If it is not feasible to design a cab that has adequate adjustability to allow the coordinates to be accessible to all, equipment manufacturers should at least avoid putting safety or time-sensitive controls near the following ISO 6682 cab coordinates: A_2r, B_2r, D_2r, E_1r, E_2r, F_1r, F_2r, A_2l, B_2l, D_2l, E_1l, E_2l, F_1l, and F_2l. A review of the ISO standards used in this study, with a view to considering human factors and safety, should be implemented.

The third part of this study combined the limitations of cab accessibility and operator reach envelope to create a realistic simulation of the reachability barriers experienced by operators in the workplace. When considering these two limitations, the best overall accessibility with and without flexion was 75.0% of all coordinates (achievable on SFLHT1 with the large ISO 3411 operator with no flexion and the medium and large operators with flexion). For the cabs and manikins assessed in this study, no situation exists in which an operator would be able to reach 100% of the comfort coordinates for hand control locations. This inequity limits workers' reaching ability and reduces their autonomy, ultimately hindering their ability to execute their job efficiently. Lastly, the worst case scenario for reach occurs for 5th percentile Latino female operators who can fully reach only 29.7% of the controls without flexion (FFDT2), or 41.7% with flexion (SFLHT2).

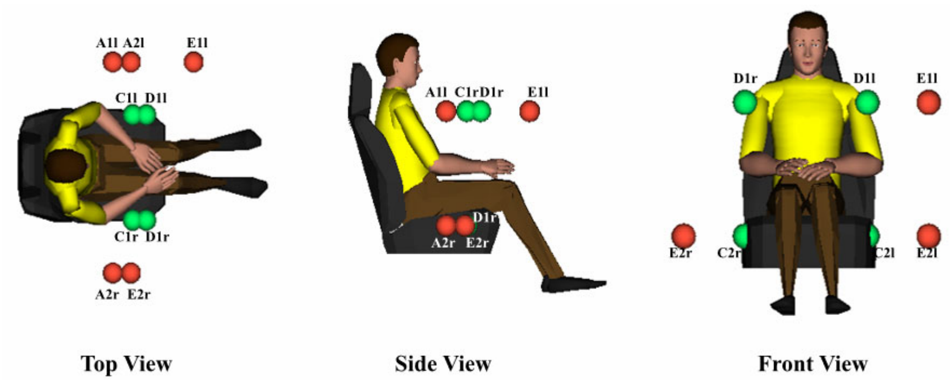
Previous research has emphasised the importance of accommodating as many users as possible when designing mining equipment and systems (Horberry et al., 2011; Keyserling et al., 1988; Schutte and Shaba, 2003). Although previous work and ISO standards have made an effort to consider the 5th percentile female to the 95th percentile male, many individuals are still excluded in these studies and standards. For instance, ISO 3411 and 6682 are based on male and female anthropometrics databases from the USA, Europe, and Asia, which excludes a large population of representative workers, as observed in the findings of this study.

Previous work by Keyserling et al. (1988) that used North American anthropometric data determined that the reach requirements in many workstations are excessive, requiring the workers to adopt non-neutral postures. Maintaining an awkward, non-neutral, working posture is linked to the development of many MSDs (Charles et al., 2018; Eger et al., 2008; Godwin et al., 2010; Goggins et al., 2022; Keyserling et al., 1988; Schutte and Shaba, 2003; Sen et al., 2020). The current study found that reachability for two under-represented populations (Indigenous and Latino females) is worse than the commonly included sub populations. A more equitable and inclusive approach to designing mining equipment and systems can be achieved by taking into account the safety and well-being of these underrepresented populations. Including minority groups in the design process is essential in retaining diversity while limiting barriers to entry (Lusebrink et al., 2021). Overall, considering diverse body types, physical abilities, and promoting inclusivity and equity can ensure that certain populations are not disproportionately affected or excluded.

The findings from this study demonstrate that awkward postures are required to reach the designated ZoC in all four vehicles analysed. Previous studies have indicated that controls should be easily reachable to reduce MSD risk to mining machinery operators (Brkić et al., 2023). This demonstrates the importance of including EDI as a foundational element in the formation of a MSD prevention plan. Further, previous work has demonstrated that in some cases, emergency stops, and other crucial controls, are out of the operator's reach or are obstructed (Schutte and Shaba, 2003). The results in this study expand on the findings of Schutte and Shaba (2003) by displaying the specific regions in ISO 6682 where emergency controls should not be placed, as they would be inaccessible for many operators. While previous work has shown the need for cab redesign (Bátiz-Flores et al., 2021; Godwin et al., 2010; Sen et al., 2020), this study advances on previous work to display both the reachable areas and problematic areas in a cab for a range of operators, as well as highlighting the importance of having an EDI perspective.

There is a need to adopt a more inclusive approach to design and appreciate human complexity to benefit these two modelled populations (Chiou and Roscoe, 2021). Designing a cab with adequate adjustability and reachability for every potential operator is challenging. However, with the seat adjustments in place, points C_1r, C_2r, D_1r, C_1l, C_2l, and D_1l were both, located inside the cab, and accessible to all five manikins. As such, important or time-sensitive, safety controls should be placed in these regions to ensure that the greatest percentage of operators can access them. Points A_2r, E_2r, A_1l, A_2l, E_1l, and E_2l were not accessible to any of the manikins in any of the cabs, either due to not falling within the cab or being unreachable by the operator. In future cab design efforts, engineers and manufacturers should avoid these points, as these regions are not accessible to the majority of operators. The result of inaccessible controls is increased risk to the operators from inequitable safety outcomes. Figure 5 displays the coordinates that were accessible to all manikins (green) and the coordinates that were not accessible to any manikins (red). These data can be helpful in addressing design barriers and motivating manufacturers to make changes to current designs to benefit all workers (Spiwak et al., 2021).

Figure 5 ISO 6682 (1986) coordinates fully accessible to all operators under all conditions (green) and coordinates not fully accessible to any manikin under any condition (red) (see online version for colours)



Cab redesign that places controls, particularly primary controls, within the reach envelope of operators based on the findings from this study would permit operators to access the controls without flexing their trunk, thus reducing their risk of developing a MSD (Godwin et al., 2010; Heine et al., 2020). Further, a more equitable and diverse approach to cab redesign can promote safety, equity, and inclusion in the workplace and create a sense of belongingness (Spiwak et al., 2021).

There are a few limitations to this study that should be considered in future work. The value used to reflect the distance between the H-point and the SIP is based on military seats. Although military machines fall into the same ISO regulations as mining machinery, the true distance between the H-point and the SIP in mining machinery may differ from the value used in this study. There may also be limitations associated with the accuracy of the cab modelled in JACK to actual cabs. Furthermore, the manikins used in this study do not reflect the endless anthropometric possibilities for operators of mobile mining machinery. However, the manikins chosen do reflect the demographics that make up the current Canadian mining population.

Using the methodology outlined in this study, future research should assess machines used in other industries that have been identified as having comfort or safety concerns, such as excavators, tractors, and trams (Bátiz-Flores et al., 2021; Ferrari and Cavallo, 2012; Heine et al., 2020; Balaji and Alphin, 2016; Kuijt-Evers et al., 2003). ISO 6682 also outlines the ZoC for foot controls and the zone of reach for hand and foot controls. More work is needed to examine the location of these zones relative to operators' hand and foot reach envelopes. Future research should also assist in the revision of ISO 6682 to adjust the ZoC to an area that is accessible to the majority of operators and advocate for the revision of ISO anthropometric standards to include more diverse anthropometric data. Finally, future work should examine if the use of reconfigurable cab designs, such as the design outlined by Zhou et al. (2003), improves the accessibility of the ZoC for hand control locations.

5 Conclusions

The current design of many mining machinery cabs built in accordance with ISO 6682 does not allow for adequate reachability for the range of operators that are representative of the current working population in North American mines. This study highlights some of the limitations and barriers to EDI that occur as a result of cab design and insists on the creation of more inclusive and adaptable cabs. In the poorest reach conditions, the smallest operator examined in this study can fully reach only 29.2% of the coordinates without flexion. The best accessibility scenario only allows the largest operator to access 75.0% of the coordinates for the ZoC within the cab enclosure. For the cabs and manikins used in this study, no situation exists in which an operator would be able to reach 100% of the ZoC for hand control locations outlined in ISO 6682. Future work needs to update the ISO standards for cab design based on the findings from this study to increase reachability and accessibility, and ultimately improve EDI in the mining industry.

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