Redefining Ergonomic Design: Human-Centered Anthropometric Modeling for Tractor Cab Optimization

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ABSTRACT

This study focuses on enhancing the ergonomic design of tractor cabs using advanced anthropometric modeling tools and a Human-Centered Design (HCD) approach. As the agricultural industry increasingly shifts towards autonomous machinery, operators' roles are evolving from active engagement to more passive oversight. This transition necessitates rethinking cab designs to prioritize operator comfort, safety, and usability. This study investigates the Active Range of Motion (AROM) for various joints (the buttocks, back, shoulders, neck, left leg, right leg, left arm, and right arm) and categorizes these into three zones: comfortable, acceptable, and unsatisfactory. Using RAMSIS software, digital twins of operators were analyzed to assess joint movement and visual field classifications. The findings provide actionable insights for positioning controls and displays within optimal comfort zones and visual cones, ensuring ergonomic efficiency. This study highlights gender-based differences in AROM and validates the symmetrical nature of joint movements across body sides. By employing these findings, designers can develop tractor cabs that meet functional demands and enhance user well-being, safety, and productivity.

RÉSUMÉ

Cette étude porte sur l'amélioration de la conception ergonomique des cabines de tracteurs à l'aide de la modélisation anthropométrique avancée et d'une approche de conception centrée sur l'humain (CCH). Comme l'industrie agricole se tourne de plus en plus vers des machines autonomes, le rôle des opérateurs évolue d'un engagement actif vers une surveillance plus passive. Cette transition nécessite de repenser la conception des cabines afin de privilégier le confort, la sécurité et la convivialité de l'opérateur. Cette étude examine l'amplitude active des mouvements (AAM) de diverses articulations (les fesses, le dos, les épaules, le cou, la jambe gauche, la jambe droite, le bras gauche et le bras droit) et les classe en trois zones : confortable, acceptable et insatisfaisante. À l'aide du logiciel RAMSIS, les jumeaux numériques des opérateurs ont été analysés pour évaluer les mouvements articulaires et les classifications du champ visuel. Les résultats fournissent des informations exploitables pour positionner les commandes et les affichages dans des zones optimales de confort et des cônes visuels, garantissant ainsi une efficacité ergonomique. Cette étude met en évidence les différences liées au genre relatives à l'AAM et valide la nature symétrique des mouvements articulaires par rapport aux côtés du corps. En utilisant ces résultats, les concepteurs peuvent développer des cabines de tracteur qui répondent aux exigences fonctionnelles et améliorent le bien-être, la sécurité et la productivité de l'utilisateur.

KEYWORDS

Human-Centered Design, Ergonomics, Anthropometric Modeling, Tractor Cabs, Operator Comfort, RAMSIS

MOTS CLÉS

Conception centrée sur l'humain, Ergonomie, Modélisation anthropométrique, Cabines de tracteur, Confort de l'opérateur, RAMSIS.

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INTRODUCTION

In recent years, autonomous machines have been developed for agricultural tasks to improve work efficiency, relieve labor intensity, and enhance the quality of production and reduce cost (Bashiri and Mann 2014; Kayacan et al. 2014; Lagnelöv et al. 2021). This shift towards autonomy has significantly altered the operator's role. Operators are transitioning from actively engaging in every aspect of driving to adopting a more passive role where they are only infrequently responsible for steering (Ganesh 2020). This trend might alter the usage patterns of the machine's control interface or introduce new tasks. Therefore, rethinking the design of the entire cab environment is essential to ensure the operator's comfort and the usability of the system. The goal is to go beyond mere functionality and design a solution that optimally serves the human operator. To address past physical ergonomic issues and align with modern cab development trends, it is crucial to move away from the traditional focus on machine performance. Instead, a more effective approach involves adopting a methodology that integrates innovative tools for designing a human-centric, ergonomically optimized cab (Flanagan et al. 1997; Grandi et al. 2022).

A Human-Centered Design (HCD) involves viewing tasks from the users' perspective to comprehend their emotions, motivations, and challenges (Steen 2011). To achieve this understanding, various methods can be employed, such as interviews, surveys, questionnaires, and observations. These techniques provide direct insights into the users' experiences. In a work by Fagnant and Kockelman (2018), the effective implications of direct HCD methods on developing autonomous ride-sharing vehicles were explored. Through comprehensive interviews with 20 participants, the research aimed to uncover patterns in their feedback, determine needs arising from these patterns, and create solutions to meet these needs. The findings resulted in the creation of tailored vehicles, ride-share solutions with space segmentation, and systems for automatic personal and ride-share configuration. Another research study (Alppay and Bayazit 2015) also applied a HCD method to develop helicopter instrument panels, focusing on the importance, frequency of use, functional similarity, and sequence of use of components. Through interviews with pilots, the researchers gathered feedback on the frequency of use, importance, and general opinions of pilots on cockpit displays. This feedback informed the creation of optimized alternative display layouts and improved functional groupings. However, while directly engaging with end-users is highly effective for designing a human-centered product and provides firsthand insights into their concerns and needs, it is crucial to have a sufficiently large sample size to make valid assumptions and generalize the findings to a broader user group. Conducting direct interviews to gather this information, while valuable, is time consuming and may not provide a sufficiently large sample size to cover all the available options.

Another aspect of HCD is to ensure the operator's comfort and safety, as highlighted by Kölsch et al. (2003) and Tilley (1993). Comfort is often described as a pleasant or relaxed state experienced by an individual in response to their environment (Vink and Hallbeck 2012), while discomfort refers to an unpleasant state of the body caused by physical factors such as muscular strain, fatigue, blood circulation issues, or pain (Zhang et al. 1996). Although there is not a universally accepted definition, it is widely acknowledged that comfort and discomfort are subjective feelings or emotions (De Looze et al. 2003; Kölsch et al. 2003). Discomfort can be detected or measured through its association with physical parameters such as joint angles, muscle strain, and fatigue. Understanding the specific ranges of motion that cause discomfort is essential to avoid positions that may lead to pain or injury. Comfort can be viewed as the absence or minimal presence of discomfort, so identifying these lower-discomfort zones helps in designing ergonomic solutions that promote ease, reduce fatigue, and support long-term operator well-being. Designing interfaces within the comfort zone prevents users from adopting alternative, potentially harmful postures (Kölsch et al. 2003). Previous efforts to model comfort and discomfort include notable contributions by Helander and Zhang (1997), De Looze et al. (2003), and Moes (2005). Helander and Zhang (1997) differentiated comfort and discomfort as separate scales, where comfort encompasses positive experiences beyond merely the absence of discomfort. De Looze et al. (2003) advanced this understanding by connecting physical product characteristics and psychosocial factors to comfort and discomfort, stressing the significance of individual expectations and environmental influences. Moes (2005) proposed a linear model detailing the progression from product interaction to discomfort experience, emphasizing internal bodily effects and perceptions. While these models provide valuable insights into the concepts of comfort and discomfort, their practical application may be limited due to inherent complexity, subjectivity, and potential oversimplifications. Therefore, ongoing refinement and incorporation of broader factors are essential to develop more universally applicable ergonomic solutions.

A suggested method to assist interface designers in maintaining subtle comfort and preference limits is to define the comfort zone as a range of postures or movements that users voluntarily adopt (Kölsch et al. 2003). While defining these zones can be achieved through interviews or direct observations, the drawbacks of these methods have been noted. To reduce reliance on direct user questionnaires and interviews, the study can utilize software (RAMSIS) developed through extensive human anthropometry research. Such a tool assesses comfort and discomfort across a large population. Utilizing available software to create digital twins of humans could be an effective strategy for an HCD approach. Digital twins allow for continuous, objective data collection and scenario simulation, providing more accurate and personalized insights into user needs than traditional direct methods like interviewing end users. This approach allows designers to define comfort zones around the human and propose a method that aides interface designers to stay within these more subtle limits of comfort and preference (Kölsch et al. 2003). It allows them to prioritize tasks according to their importance around the user, enhancing design efficiency, and facilitating data-driven decisions for a superior user experience.

Objectives The initial step in better understanding the human operator is identifying where they experience the most comfort and the least discomfort. By designing interfaces within established comfort zones, the goal is to minimize the strain on muscles and joints. Therefore, this study aims to identify areas around these key joints that are classified as comfortable, acceptable, and unsatisfactory, while also examining the visual comfort cone of the human operator.

METHODOLOGY

Correlation of Joint Motion to Discomfort

The RAMSIS NextGen (Version 10) software was used to develop two digital twins of a human operator (i.e., one representing a 95th percentile male and one representing a 5th percentile female) based on the work of Lewis and Narayan (1993) and using a North American anthropometry database (Table 1). These percentiles were selected to encompass a broad range of body sizes. The digital twin was utilized to analyze typical seated driving postures on the basis of task-related discomfort; this was possible because the RAMSIS NextGen software contains a database with perceived discomfort in various body positions that was populated by completion of a standardized questionnaire (Kris and Dodd 2004) by human participants. The RAMSIS NextGen software assigns discomfort ratings on an 8-step ordinal scale for any joint angle. A significant difference in discomfort perception among subjects is indicated by a difference of one complete step (e.g., between 2.5 and 3.5 on the 8-step ordinal scale) following an exponential relationship. Discomfort ratings were calibrated so that the most probable driving posture (RAMSIS' neutral posture) corresponded to the posture with the least discomfort.

While only a subset of anthropometric dimensions is listed in Table 1 for reference, the RAMSIS digital human model incorporates a comprehensive set of anthropometric data, including segment lengths, joint centers, and posture-relevant measurements such as shoulder height, eye height, hand length, and elbow position. These detailed parameters are embedded in the digital twin to ensure realistic simulation of human movement and evaluation of discomfort.

The movements of each joint have specific, well-defined names. For instance, shoulder flexion refers to the movement that decreases the angle between the arm and the front of the body, essentially raising the arm forward and upward from a resting position at the side. Each joint exhibits various movements, some with unique names and others that may overlap. To simplify understanding and avoid using multiple names for each joint movement, a coordinate system was assigned to each joint movement as predefined by the RAMSIS software (Fig. 1). This study investigated the range of motion across all joints associated with the buttocks, back, shoulders, neck, left leg, right leg, left arm, and right arm (Fig. 1). Each joint is considered to be located at [0,0,0] degrees in this system. For instance, -40° movement in the shoulder joint's y-direction means flexion. Another example is the elbow joint's range of motion [-95°, 85°] in the x direction; -95° stands for internal (medial) rotation while 85° stands for external (lateral) rotation.

For this study, we systematically measured the active range of motion for each joint (i.e., shoulder, elbow, wrist, hip, knee, ankle and cervical) (Fig. 1) on both left and right sides of the body, assigning a numerical comfort/discomfort value to every degree of movement. Each recorded value corresponded to a specific level of perceived discomfort or comfort, allowing for a precise evaluation of how joint movement influenced user comfort. The classification of discomfort ratings was derived from the RAMSIS software manuals, which provided the basis for determining comfort thresholds. According to this framework, values between 0 and 1.7 were rated as "comfortable", values from 1.7 to 2.5 were rated as "acceptable", and values above 2.5 (up to 8) were rated as "unsatisfactory".

Correlation of Visual Field of View to Discomfort

A detailed analysis of the comfortable vision cone was completed by defining and examining the sharp sight cone, optimum visual field cone, and maximum visual field cone. The neutral driving posture for truck operators was chosen as a reference due to its similarity to agricultural tractor postures.

RESULTS

Zone classification

The range of motion for each joint, on both sides of the body, and for male and female is summarized in Table 2. When rounded to the nearest whole number, both sides exhibit the same AROM (Active Range of Motion). A slight difference in the range of motion of male and female subjects was observed in the shoulder joint.

Table 1. The body dimensions of the 95th percentile male and 5th percentile female for the 18-70 age group (2010 reference year)*.

Body Feature	95th Percentile Male	5th Percentile Female
Body height (cm)	187.66	151.58
Waist circumference (cm)	103.50	57.72
Sitting height (cm)	98.24	79.73

* Only a subset of anthropometric dimensions is listed

Table 2. The active range of motion for each joint is presented in degrees, with the neutral position of each joint defined as 0 degrees.

Joint	Range of Motion (X)		Range of Motion (Y)		Range of Motion (Z)	
	Male	Female	Male	Female	Male	Female
Right Shoulder	[-57, 18]	[-90, 18]	[-124, 13]	[-124, 17]	[-156, 9]	[-156, 6]
Left Shoulder	[-18, 57]	[-18, 90]	[-13, 124]	[-17, 124]	[-156, 9]	[-156, 6]
Right Elbow	[-95, 85]	[-95, 85]	[-87, 59]	[-87, 59]	–	–
Left Elbow	[-85, 95]	[-85, 95]	[-87, 59]	[-87, 59]	–	–
Right Wrist	–	–	[-73, 87]	[-73, 87]	[-40, 29]	[-40, 29]
Left Wrist	–	–	[-87, 73]	[-87, 73]	[-40, 29]	[-40, 29]
Right Hip	[-48, 48]	[-48, 48]	[-34, 41]	[-34, 41]	[-102, 38]	[-102, 38]
Left Hip	[-48, 48]	[-48, 48]	[-41, 34]	[-41, 34]	[-102, 38]	[-102, 38]
Right Knee	[-20, 40]	[-20, 40]	[-63, 77]	[-63, 77]	–	–
Left Knee	[-40, 20]	[-40, 20]	[-63, 77]	[-63, 77]	–	–
Right Ankle	[-24, 23]	[-24, 23]	–	–	[-27, 49]	[-27, 49]
Left Ankle	[-23, 24]	[-23, 24]	–	–	[-27, 49]	[-27, 49]
Cervical	[-30, 30]	[-30, 30]	[-12, 12]	[-12, 12]	[-23, 37]	[-23, 37]

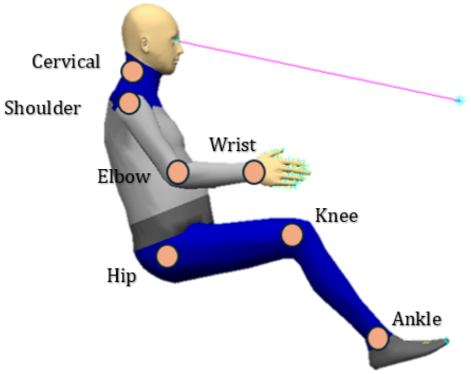

Fig. 2. The joints highlighted with dots are the primary focus of the study.

The aforementioned AROM was then further divided into three zones: comfortable, acceptable, and unsatisfactory, as shown in Table 3. The classifications were determined by the degree of joint movement, with discomfort ratings assigned as follows: 0-1.7 were rated as comfortable, 1.7 to 2.5 were considered acceptable, and ratings above 2.5 up to 8 were deemed unsatisfactory. These values were determined using the RAMSIS software, with the range of 1.7 to 2.5 being established based on moderate levels of perceived discomfort.

It can be interpreted from Table 3 the male right shoulder's comfort range is well-defined within a moderate X range [−10, 10°], a narrow Y range [−5, 5°], and a broad Z range [−91, 9°] for a male operator. The acceptable range includes additional extended regions on both ends for all axes: [−41,−11°], [11, 15°] for X, [−59,−6°], [6, 27°] for Y, and [−92,−115°] for Z. Unsatisfactory positions are observed in the extreme low and high ranges: [−57,−42°], [16, 18°] for X, [−124,−60°], [28, 36°] for Y, and [−156,−116°] for Z.

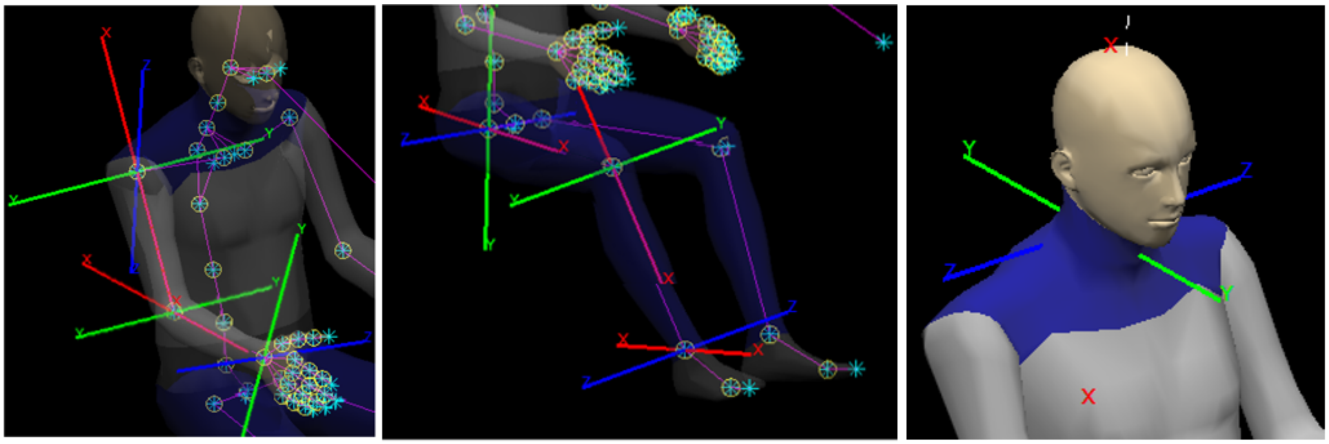

Fig. 3. Assigned coordinates systems to shoulder, elbow, wrist, hip, knee, ankle and cervical joint created by RAMSIS.

Table 3. Classification of male joint ranges of motion for across three axes (X, Y, Z).

Joint	Zone	Range of Motion (X)	Range of Motion (Y)	Range of Motion (Z)
Shoulder	Comfortable	[-10, 10]	[-5, 5]	[-91, 9]
	Acceptable	[-41, -11], [11, 15]	[-59, -6], [6, 27]	[-92, -115]
	Unsatisfactory	[-57, -42], [16, 18]	[-124, -60], [28, 36]	[-156, -116]
Elbow	Comfortable	[-67, 60]	[-2, 2]	-
	Acceptable	[-81, -68], [61, 71]	[-19, -3], [3, 19]	-
	Unsatisfactory	[-95, -82], [72, 85]	[-87, -20], [20, 59]	-
Wrist	Comfortable	-	[-36, 42]	[-7, 20]
	Acceptable	-	[-52, -37], [43, 61]	[-18, -8], [21, 24]
	Unsatisfactory	-	[-73, -53], [62, 87]	[-40, -19], [25, 29]
Hip	Comfortable	[-6, 6]	[-20, 24]	[-20, 18]
	Acceptable	[-24, -7], [7, 24]	[-25, -21], [25, 30]	[-39, -21], [19, 25]
	Unsatisfactory	[-48, -25], [25, 48]	[-34, -26], [31, 41]	[-102, -40], [26, 38]
Knee	Comfortable	[-12, 23]	[-50, 61]	-
	Acceptable	[-13, -15], [24, 29]	[-53, -51], [62, 64]	-
	Unsatisfactory	[-20, -16], [30, 40]	[-63, -54], [65, 77]	-
Ankle	Comfortable	[-17, 17]	-	[-24, 11]
	Acceptable	[-20, -18], [18, 19]	-	[-28, -25], [12, 20]
	Unsatisfactory	[-24, -21], [20, 23]	-	[-38, -29], [21, 38]
Cervical	Comfortable	[-20, 20]	[-5, 5]	[-12, 17]
	Acceptable	[-25, -21], [21, 25]	[-8, -6], [6, 8]	[-17, -13], [18, 27]
	Unsatisfactory	[-30, -26], [26, 30]	[-12, -9], [9, 12]	[-23, -18], [28, 37]

A more detailed examination of the defined zones in the x-z plane and y direction is presented in Fig. 3. Red represents unsatisfactory, yellow indicates acceptable, and green signifies comfortable positions. This figure illustrates that a 10° hand movement in the y direction falls within the comfort range, while movements of 54 and 22° further are still within the acceptable range. Movements beyond this range may cause higher levels of discomfort. Additional illustrations of these zones are provided in Fig. 4, which showcase a wide comfort zone in the z direction, covering 100°. The same process has been done for the hip joint (Fig. 5).

Visual field classification

According to the analysis done using RAMSIS NextGen software, the visual capabilities of a normal-sighted observer are outlined by specific opening angles that define various viewing cones. These cones represent different aspects of visual perception, each with distinct characteristics (Fig. 6).

The Sharp Sight Cone (Green) has an opening angle of 2.5° and defines the area where the observer can perceive details with high clarity. It begins at the center of the eye and extends through the fixation point, with the diameter of the cone expanding proportionally as the distance from the eye to the fixation point increases. The Optimum Visual Field Cone, with an opening angle of 15°, represents the optimal viewing range for visual comfort, allowing eye movements while keeping the head static. This range is defined for binocular vision and enables the observer to comfortably perceive their environment. The Maximum Visual Field Cone, with an opening angle of 50°, indicates the maximum viewing range where the observer relies on peripheral vision. It is a monocular field (for either the left or right eye) and provides the maximum extent of the visual field while keeping the head stationary.

DISCUSSION

The results presented in the previous section provide a comprehensive overview of the AROM for various joints, their categorization into comfortable, acceptable, and unsatisfactory zones, and visual field classifications. This discussion will delve into the implications of these findings, their alignment with existing literature, and potential applications in ergonomic design.

Gender and side differences

The detailed comparison of AROM between males and females, and between the right and left sides of the body, shows that while both genders exhibited similar trends, there were slight differences, particularly in the shoulder

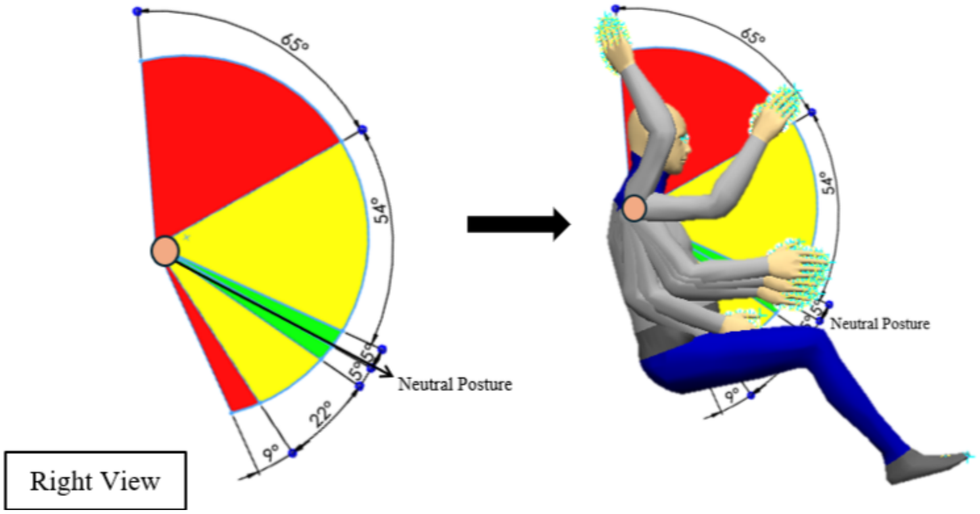

Fig. 3. The defined zones of comfort, acceptable, and unsatisfactory ranges around the right shoulder joint are illustrated with a right-side view of a created manikin (y direction).

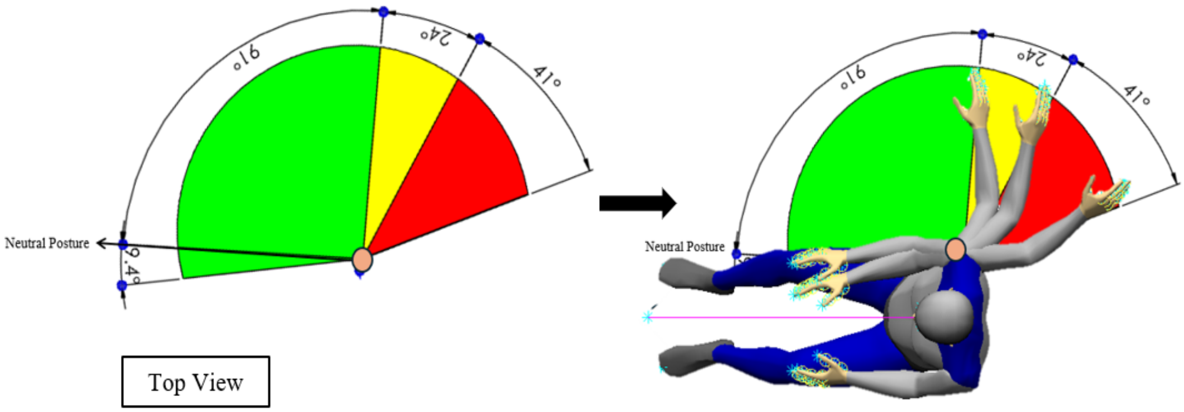

Fig. 4. Top View: Showcasing the plane of motion range of the right shoulder joint in the z direction.

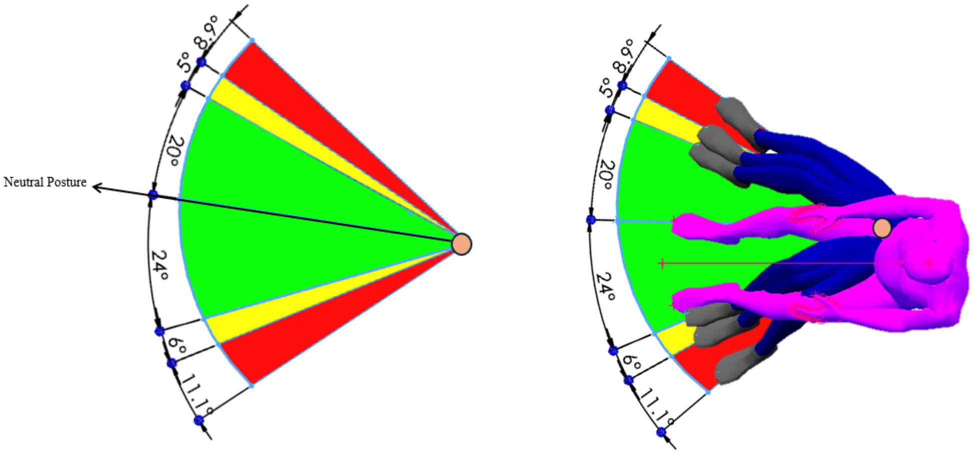

Fig. 5. The top view of the hip joint movement illustrates the defined zones of comfort, acceptable, and unsatisfactory ranges.

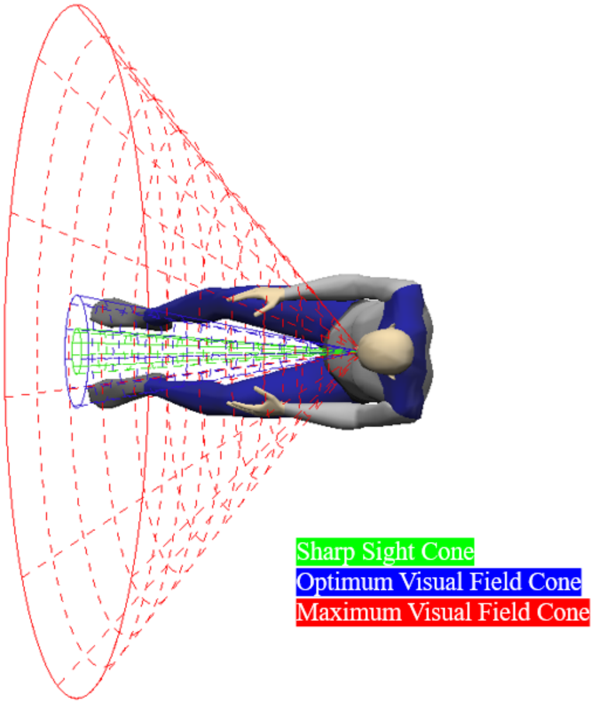

Fig. 6. The visual field is segmented into three zones: the sharp sight cone, the optimum visual field cone, and the maximum visual field cone (respectively from the inside to the outer side).

joint. The observed greater AROM in females' shoulders is supported by the work of Sahrmann et al. (2017) who found that joint laxity is often higher in females due to hormonal differences affecting connective tissue. Additionally, studies have shown that joint movements for females are slightly higher than for males; for example, ankle inward movement was reported to be 36.0° for male subjects, while 38.1° was reported for females aged 16-30 (Chung and Wang 2009). This study also argues that females demonstrate higher ROM in the cervical spine, upper extremity, and lower extremity joints compared to males. The greater AROM in females could be attributed to hormonal differences, anatomical and physiological factors, and lifestyle variations (Vink and Hallbeck 2012). However, the software used in this study to develop AROM for males and females did not consistently recognize these slight differences, except in the shoulder joint. Although gender differences in AROM were not consistently recognized, the overlap in smaller ranges between males and females suggests that these shared values should be considered as a baseline for common design practices. Designing for this overlapping range ensures inclusivity and accommodates the needs of a broader population, rather than tailoring designs strictly based on gender-based differences that may not be universally significant.

In this study, no differences were found in the AROM between the left and right sides of the body. Similar observations were reported by Roaas and Andersson (1982) who found no statistically significant difference between the motions of the right and left sides of the body. This indicates that the range of motion in these joints is generally symmetrical in healthy individuals within the specified age group. These insights contribute to a more nuanced understanding of AROM variations across genders and body sides.

Zone classification and implications

In today's world, where the comfort and well-being of device operators are prioritized, and HCD has gained more attention, there has been an increasing effort to simplify the subjective concept of comfort into qualitative values. This helps to better understand this complex phenomenon and apply it effectively in interior design of future cars, tractors, and other vehicles. Various attempts, such as the development of indexes like RULA (Rapid Upper Limb Assessment), REBA (Rapid Entire Body Assessment) (Ansari and Sheikh 2014; McAtamney and Corlett 1993), and LUBA (Loading on the Upper Body Assessment) (Kee and Karwowski 2001), have been made to better understand posture. However, these methods often involve limited scope or complex mathematical models and require computational resources, which may not be easily accessible or practical for all designers or manufacturers. Another attempt was made by Naddeo and Memoli (2009) to develop an index specifically for evaluating arm movements, but the evaluation focuses on the posture of a single arm.

The goal of this research was to simplify this process further so that engineers and researchers can easily identify the comfortable, acceptable, and unsatisfactory ranges around the human body. The proposed method is to assist interface designers in adhering to the more subtle limits of comfort and preference. The zones were defined as follows:

- Comfortable Range: Movements within this range are likely to be pain-free and sustainable over long periods,
- Acceptable Range: Movements within this range are tolerable but may cause discomfort if sustained for long periods, and
- Unsatisfactory Range: Movements within this range are likely to cause discomfort or pain and are not recommended for sustained periods.

The idea behind defining these zones is to aid design engineers in assigning tasks relative to their importance within one of these zones. For example, the hip joint has a comfortable range of -31 to 12°, suggesting that features requiring hip movement should be placed within these angles (Fig. 7). Similarly, for the shoulder joint, tasks requiring shoulder movement should be within a range of -5 to 5° for up and down movements, and -91 to 9° for outward to inward movements (Fig. 8).

By identifying these areas around the human operator, engineers can assign tasks based on their importance within one of the specified zones. This approach helps designers create products and workspaces that enhance user comfort and well-being. Understanding and adhering to acceptable

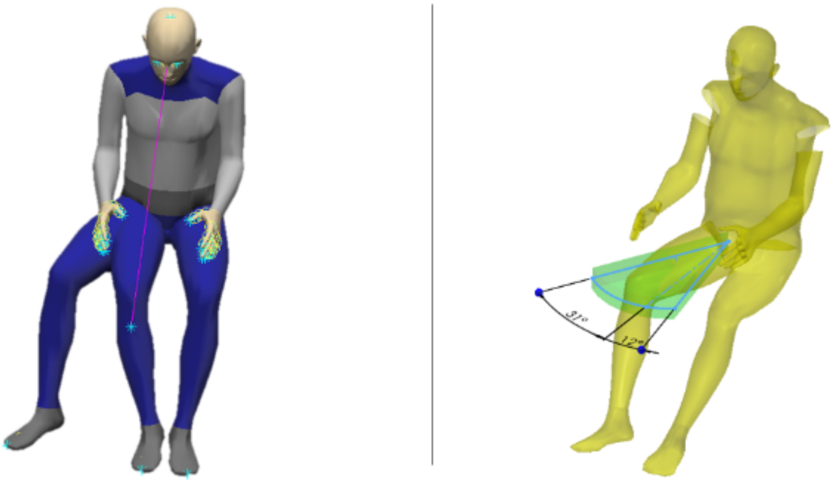

Fig. 7. The defined comfort zones of hip joint movement in 3D environment.

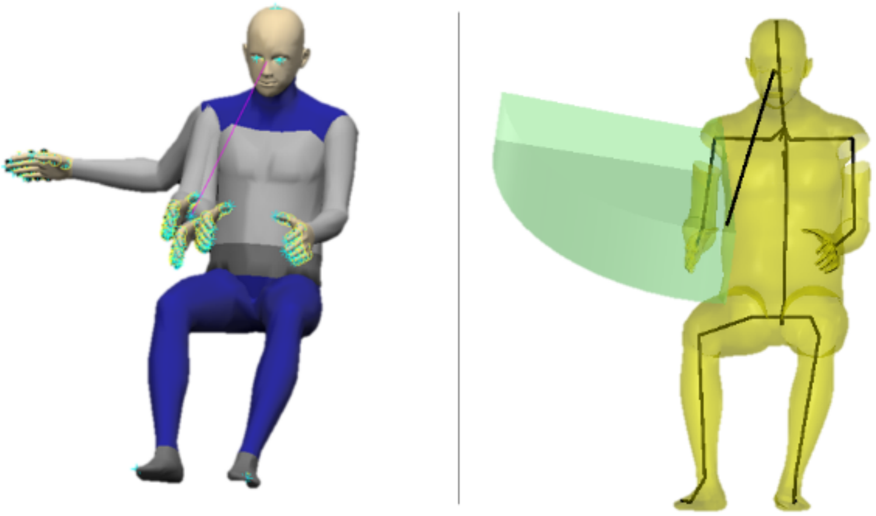

Fig. 8. The defined comfort zones of shoulder joint movement in 3D environment.

joint motion ranges can help reduce the risk of repetitive strain injuries and other musculoskeletal disorders. Objective data on joint movement ranges can inform better decision-making in design, leading to more effective ergonomic solutions. This method allows for the development of customizable ergonomic solutions tailored to specific tasks, user groups, or individual needs.

As agricultural machinery increasingly incorporates partial or full autonomy, the operator's role and required interactions with machine controls and displays will evolve. Autonomous tractors may feature a reduced number of actuators and indicators, changing where and how operators interact with the cab environment. In this context, the defined comfort zones and joint movement ranges can guide the optimal placement of these fewer but critical controls, ensuring they remain within ergonomic reach and minimize operator strain during supervisory or occasional intervention tasks.

Visual field classification

The visualization of sight cones offers a detailed understanding of how visual perception shifts with varying viewing angles and distances. The sharp sight cone, corresponding to central vision, is where visual acuity is highest, making it essential for tasks requiring precision and detail. The optimum and maximum visual field cones extend around the sharp sight cone, enhancing situational awareness by detecting peripheral movement and providing context to central vision (Fig. 6). The optimal field of view is best suited for the placement of important displays and controls, as it facilitates quick eye movements and minimizes the need for significant head or body movements, thereby enhancing efficiency and comfort, especially in environments where rapid and accurate visual access is critical. By comprehending these visual fields, designers can strategically position tasks and information within these cones based on their significance and frequency of use, ensuring that key and frequently accessed information is placed within the sharp or optimum visual cone for optimal accessibility.

Additionally, lines of sight to the front, sides, and rear of the vehicle remain essential for operator situational awareness, even with increased automation. Understanding the operator's visual field classification allows designers to position displays and warning signals effectively, accommodating the operator's need for quick, unobstructed views while monitoring autonomous machine operations. These considerations ensure that ergonomic and human-centered design principles continue to support safety and comfort as machine autonomy advances.

Application as a design tool

While ergonomics and human-centered design principles have long been integrated into the design of agricultural tractor operator stations, current approaches often rely on generalized guidelines that may not fully account for detailed anthropometric variability and joint-specific comfort zones. This research advances the field by providing granular, joint-level ergonomic data and clearly defined comfort, acceptable, and unsatisfactory zones based on extensive anthropometric analysis. By applying these precise data-driven criteria, designers and manufacturers can optimize control placement, seating, and display configurations to a degree of specificity not typically addressed in existing design standards.

Furthermore, the incorporation of visual field classification tailored to tractor cab environments ensures that critical information is consistently positioned within the operator's optimal sight cone, enhancing situational awareness and reducing reaction times. Collectively, these improvements translate into significant benefits including reduced operator fatigue, minimized physical strain, improved safety outcomes, and increased operational productivity. By enabling more tailored and evidence-based ergonomic interventions, this approach supports the development of tractor cabs that better meet diverse operator needs, ultimately advancing the state of human-centered agricultural vehicle design.

Future research

The findings from this study have significant implications for ergonomic design and occupational health. By understanding the specific ranges of motion that are most comfortable and those that lead to discomfort, designers can create work environments and tools that promote better postures and reduce the risk of injury. However, this was an initial step for defining these zones based on the AROM. Future research could expand on these findings by exploring dynamic tasks and different postures, as well as incorporating a larger and more diverse sample population to enhance the generalizability of the results. Also, the software typically recognizes the degree of joint movement comfort and discomfort similarly for both the male 95th percentile and the female 5th percentile, as well as for visual field classifications. This is a matter that certainly warrants further discussion. Furthermore, the differences in comfort and discomfort rates on both the right and left sides of the body were found to be almost the same. This matter should also be examined in future research. By using these findings as a foundation, tractor manufacturers and ergonomic designers can create cabs that go beyond functional requirements, prioritizing comfort, safety, and efficiency.

CONCLUSION

This research delved into the anthropometric modeling of tractor cabs with a focus on ergonomic design to enhance the comfort and safety of human operators. By adopting a Human-Centered Design approach and focusing on ergonomic optimization, it is possible to enhance the comfort and safety of the operator, and the functional productivity of tractor cabs. The study provides valuable insights into the Active Range of Motion for various joints.

The research also emphasizes the significance of gender and side differences in Active Range of Motion, revealing that while both genders exhibit similar trends, females generally have a greater range of motion in certain joints. Additionally, the study found no significant differences between the Active Range of Motion of the right and left sides of the body, indicating symmetrical joint movements in healthy individuals. Further in the research, the Active Range of Motion for the shoulder, elbow, wrist, hip, knee, ankle, and cervical joints were categorized into three zones: comfortable, acceptable, and unsatisfactory. Defining comfort zones for joint movements allows design engineers to prioritize tasks based on their importance and assign them within the specified zones, thereby enhancing user comfort and well-being. The visual field classifications further support this by providing guidelines for optimal placement of displays and controls, ensuring that key information is within the most accessible visual cones.

Overall, this research provides a foundational framework for designing ergonomically optimized tractor cabs. By leveraging advanced anthropometric modeling tools and understanding human factors, designers can significantly enhance the operator's experience, ultimately improving productivity, safety, and overall well-being in agricultural operations.

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