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ERGONOMIC DESIGN OF CAB STRUCTURE FOR WHEELED COMBINE HARVESTER

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KEYWORDS

Combine harvester, Ergonomics, Cab, Working parameters, Human comfort

ABSTRACT

In view of the fact that the design of the cab structure of wheeled combine harvesters in China lacks ergonomic design parameters exclusive for Chinese drivers, there are generally problems such as high vibration and poor comfort of the whole machine structure during the harvesting process. Firstly, this paper designed the cab structure of a wheeled grain combine harvester based on ergonomics. Then, the driver's handling comfort and visibility were simulated and analyzed using Creo. Finally, the relevant dimensions of the driver's control device were optimized. The results show that the wheeled grain combine harvester cab based on ergonomic design better meets their driving comfort needs. In addition, it is found that the operating frequencies of the key components, such as the main shaft of the conveyor spindle, the vibrating screen, the threshing drum, and the intermediate shaft of the engine, partially overlap with the frequency of human discomfort. Therefore, modal planning is also needed for this harvester to meet human comfort requirements better. This paper provides the basic parameters for the design of the cab structure of the combine harvester with high comfort for the Chinese harvesting machinery driver.

INTRODUCTION

With the improvement of the technical level of agricultural machinery in China, the operator's requirements for combine harvesters are not only limited to quality and efficiency but also have higher requirements for the comfort of driving and operation (Xu et al., 2019). Drivers often work in a high-temperature and dusty environment for a long time, such that 80% of drivers will suffer from back damage due to incorrect driving posture (Bordignon et al., 2018). Additionally, since the combine harvester driving control device is the control platform for the driver to operate the harvester, which is also a typical human–machine environment system, the design of this driving control device should not only meet the performance requirements of mechanical design but also be combined with ergonomic theory to effectively consider the driver's driving comfort and convenience of operation (Naddeo et al., 2021).

Many scholars have conducted studies related to ergonomics in the cab. Liming et al. (2018) applied particle damping technology to the driver seat base of a mining truck. They found that particle damping technology could reduce cab vibration to a large extent. Therefore, they proposed a method to reduce cab vibration by using this technology. Liao et al. (2021) established a construction machinery cab seat suspension mechanism based on a negative stiffness structure, which has good vibration isolation performance and improves the driver's riding comfort and working conditions. Grandi et al. (2022) constructed a virtual scenario. They applied this scenario to the dashboard design of tractors and trucks, improving the driver and handling comfort effectively. Nguyen et al. (2019) proposed an optimal fuzzy control method for the semi-active cab hydraulic support. Thus, the driver's riding comfort was improved by optimizing the semi-active cab hydraulic mount.

Some scholars have also researched the impact of road excitation on driver comfort. Wang et al. (2020) analyzed the effects of pavement roughness, interlayer bonding conditions, bus weight, bus speed, and seating on human comfort. They concluded that pavement roughness

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had the greatest impact on human comfort. Jiang et al. (2019) evaluated the impact of road excitation on human comfort when the harvester was working. They found that driver discomfort increased as the harvester speed and road hardness and roughness increased. In addition, He et al. (2019) analyzed the parameters of the Chinese human body based on the principle of ergonomics. They found that the reasonable range of the H point and AHP point of Chinese people is different from the range given by SAE. Then they found the H point suitable for Chinese people, thus providing a reference for the design of Chinese car cabs.

At present, the structural dimensions of the harvester cabs in most countries are designed with reference to the advanced combine harvester in European and American countries. Therefore, there is no complete design parameter of the cab structure that is suitable for human body sizes in other countries. This paper takes ergonomics as the theoretical basis, using the Chinese human body size as an example to design and optimize a cab that conforms to the Chinese human body structure parameters. Therefore, this article can also provide basic calculation methods for the design parameters of cab structures in other countries.

MATERIAL AND METHODS

Ergonomics

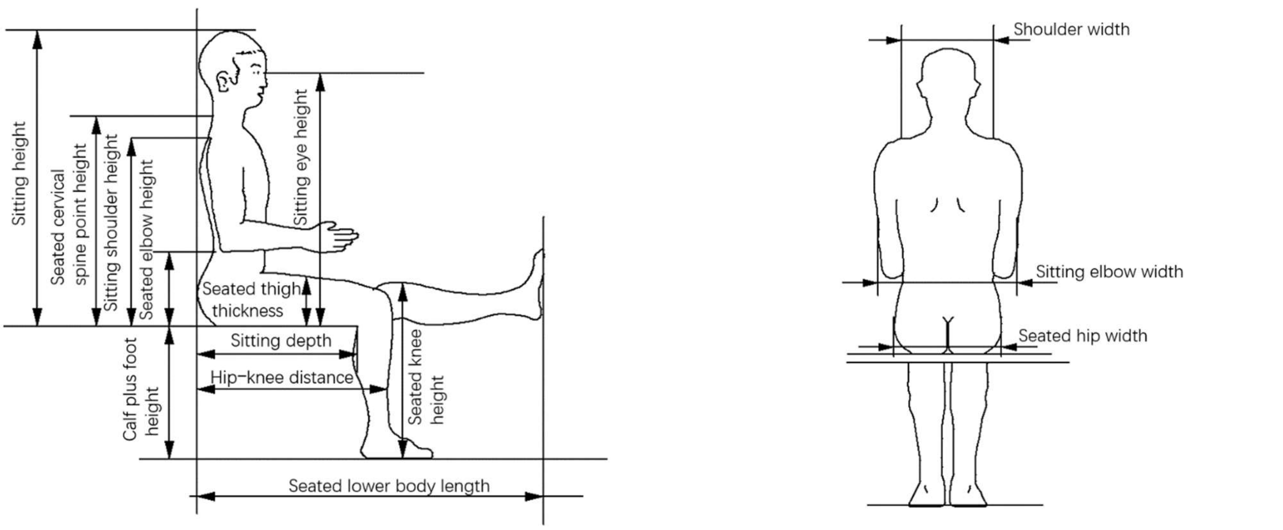
Ergonomics is a comprehensive discipline and regards the human–machine–environment system as the main research object. Ergonomics can allocate the various operational tasks reasonably required by both machines and people by studying their nature and characteristics. It ensures that machines and people can adapt to each other so that people have a comfortable and safe working environment (Soares, 2006). At present, many scholars take ergonomics as the theoretical basis to optimize the design of the cab. For example, theoretical knowledge of ergonomics exists in the design of cabs, evaluating the comfort level of the cab, and the research on the vibration comfort of the harvester under different road excitation conditions (Jiang et al., 2019; Tang et al., 2020 a; Chen et al., 2020).

Anthropometrics

Anthropometrics considers in depth the characteristics, types, and development of the human by measuring parts and the whole of the human body, which can provide a basis for the research of mechanical design, ergonomics, and the national defense industry (Kukharev & Kaziyeva, 2020; Tang et al., 2020 b; Tomkinson et al., 2017; Romelfanger & Kolich, 2019).

Percentiles of anthropometric data

The percentiles are the body size grades divided by anthropometric data, which is represented by the symbol PK. P5, P50, and P95 are commonly used percentiles for anthropometric data. P95 indicates a tall body size, P50 a medium body size, and P5 a short body size. The main dimensional parts of the human body are shown in Figure 1.



(a) The main dimensions of the human body in the sitting posture (b) The main dimensions of the human body level

FIGURE 1. Main dimensional parts of the human body.

Chinese adult human body size

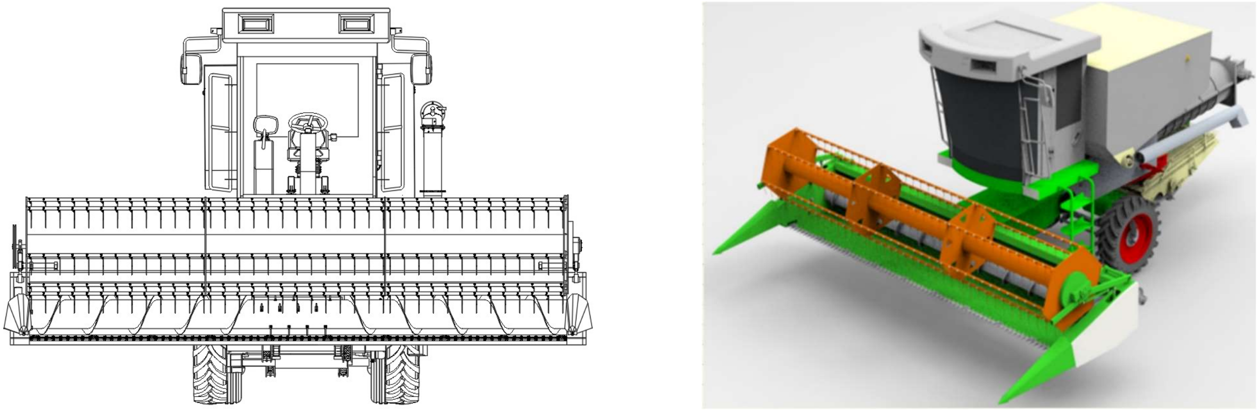
The design calculation of this paper is based on the current Chinese GB/T 10000-1988 "Human dimensions of Chinese adults". The specific size and corresponding position are shown in Table 1.

TABLE 1. Structural dimensions of the Chinese human body (mm).

Item content	Men (18–60 years old)			Women (18–55 years old)		
	5th percentile	50th percentile	95th percentile	5th percentile	50th percentile	95th percentile
Sitting height	858	908	958	809	855	901
Seated cervical spine point height	615	657	701	579	617	657
Sitting eye height	749	798	847	695	739	783
Sitting shoulder height	557	598	641	518	556	594
Seated elbow height	228	263	298	215	251	284
Seated thigh thickness	112	130	151	113	130	151
Seated knee height	456	493	532	424	458	493
Calf plus foot height	383	413	448	342	382	405
Sitting depth	421	457	494	401	433	469
Hip–knee distance	515	554	595	495	529	570
Seated lower body length	921	992	1063	851	912	975
Seated hip width	295	321	355	310	344	382
Shoulder width	344	375	403	320	351	377
Sitting elbow width	371	422	489	348	404	478

Overall structure and movement parameters of combine harvester

In order to design a wheeled combine harvester suitable for the Chinese human body size, the cab and the whole machine assembly structure of the wheeled wheat combine harvester designed in this paper are shown in Figure 2. The main parameters and fundamental frequency of the whole machine are shown in Table 2.



(a) The structure of the combine harvester (b) The model of the combine harvester

FIGURE 2. Structure of wheeled wheat combine harvester.

TABLE 2. Main motion parameters and fundamental frequency of wheeled wheat combine harvester.

Serial number	Working part name	Motion average speed (rpm)	Excitation reference frequency (Hz)	Working frequency range (Hz)
1	Crankshaft	2400.00	40.00	32.00~40.00
2	Input shaft of gearbox	3000.00	50.00	40.00~50.00
3	Intermediate shaft of engine	1425.00	23.75	19.00~23.75
4	Tangential flow drum	800.00	13.33	10.67~13.33
5	Longitudinal axial flow drum	800.00	13.33	10.67~13.33
6	Conveyor spindle	350.00	5.83	4.67~5.83
7	Header auger	80.00	1.33	1.06~1.33
8	Reel	28.50	0.48	0.38~0.48
9	Cutter	411.00	6.85	5.48~6.85
10	Fan	1240.00	20.67	16.53~20.67
11	Vibrating screen	411.00	6.85	5.48~6.85
12	Horizontal auger	1024.00	17.07	13.65~17.07
13	Vertical auger	1024.00	17.07	13.65~17.07

H-point determination of torso and thigh

This paper first refers to the recommended range of values in the current Chinese GB/T6235-2004 "Agricultural tractors - Operator’s seating accommodation - Dimensions". Then, the vertical distance from the H point (the connection point between the human torso and thigh) to the AHP point (accelerator pedal heel point) is taken as 490 mm, which is expressed by Z. In addition, the combine harvester is a B-type vehicle according to SAE (Society of Automotive Engineers). The suitable H point curve for B-type vehicles is shown in Figure 3. Therefore, the horizontal distance from the H point to the AHP point under the corresponding percentile can be obtained according to the height of the H point.

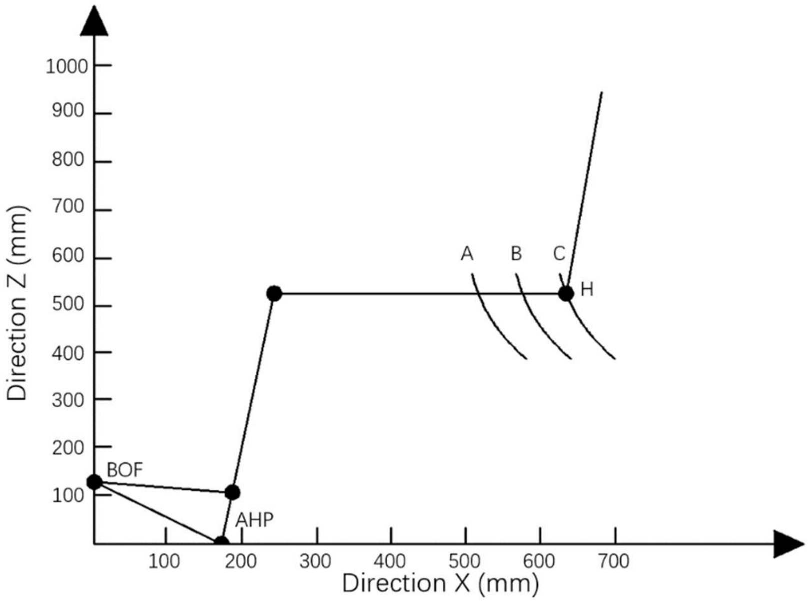


FIGURE 3. H-point position curve of B-type vehicles.

The horizontal distance from the 95th, 50th, and 5th percentile H points to the AHP is given by:

$$\begin{cases} X_{95} = 922.49 - 0.494Z \\ X_{50} = 855.31 - 0.509Z \\ X_5 = 762.17 - 0.485Z \end{cases} \quad (1)$$

where:

X_{95} represents the horizontal distance from the H point to the AHP point for a tall body size (P95),

X_{50} represents the horizontal distance from the H point to the AHP point for a medium body size (P50), and

X_5 represents the horizontal distance from the H point to the AHP point for a short body size (P5).

The amount of horizontal adjustment of the seat is noted as ΔX, which can be derived from the already calculated X_{95}, X_5.

$$\Delta X = X_{95} - X_5 = 155.91\ mm$$

To sum up, in the combine harvester cab, the coordinates of the H point are (680 mm, 490 mm), and the amount of front-to-back adjustment of the driver's seat is 156 mm.

Design of cab seat

In this paper, the main dimensions of the design of the cab seat are based on ergonomics, using the current Chinese GB/T6235-2004 "Agricultural tractors - Operator’s seating accommodation - Dimensions" as the basis. Additionally, it is combined with the human body dimensions of Chinese adults. The design parts and corrections of the seat design can be seen in Table 3. The dimensions of the reference items can be seen in Table 1.

TABLE 3. Seat design parts and corrections.

Serial number	Design parts	Reference items	Corrections (mm)
1	Seat height Y_1	Calf plus foot height	Shoe height ΔL_1=30
2	Seat depth Y_2	Sitting depth	Clothes ΔL_2=12
3	Seat width Y_3	Seated hip width	Clothes ΔL_3=12
4	Backrest height Y_4	Sitting shoulder height	Clothes ΔL_4=12
5	Backrest width Y_5	Shoulder width	Clothes ΔL_5=12

The distribution regularity of human body size (X_i) conforms to a normal distribution (Kozłowski & Gawelczyk, 2002), X_i: $N(\mu,\sigma^2)$, where

$$\mu = E(\overline{X_i}) = E\left(\frac{1}{n}\sum_{i=1}^{n} X_i\right) \quad (2)$$

Therefore, it can be known from [eq. (2)] that the dimensions of some parts of the driver's seat are equal to the expectations of the corresponding body part dimensions.

Design of seat height

If the seat height is designed reasonably, the height of the lower leg should be higher than the seat height when the driver sits down because this can ensure that the force on the driver's thighs is reasonable and his/her leg muscles are relaxed.

According to [eq. (2)], Table 1, and Table 3, the seat height Y_1 can be calculated as follows:

$$E(\overline{X_1}) = E\left(\frac{1}{6}\sum_{i=1}^{n} X_i\right) = E\left(\frac{1}{6}\sum_{i=1}^{n}(383 + 413 \ldots + 405)\right) = 395.5\ mm$$

$$Y_1 = E(\overline{X_1}) + \Delta L_1 = 395.5 + 30 = 425.5\ mm$$

Therefore, the seat height was set to 420 mm during the design process.

Design of seat depth

A reasonable seat depth not only allows the seatback to better support the driver's lumbar spine but also reduces the pressure on the sitting bones. The seat depth design is based on the 5th percentile seat depth of women so that the combine harvester can meet the comfort requirements of most people. According to Table 1 and Table 3, the seat depth Y_2 can be calculated as follows:

$$Y_2 = Y_{2min} + \Delta L_2 = 401 + 12 = 413\ mm$$

Therefore, the seat depth was set to 410 mm during the design process.

Design of seat width

In order to make the combine harvester seat meet the needs of the widest human body size, the seat width was designed using the 95th percentile female sitting hip width dimension as a reference in this paper.

According to Table 1 and Table 3, the seat width Y_3 can be calculated as follows:

$$Y_3 = Y_{3max} + \Delta L_3 = 382 + 12 = 394\ mm$$

In order to prevent the driver's hips from slipping out of the cushion in the case of turning or an uneven road surface, the seat width should be appropriately widened. Therefore, the seat width was set to 430 mm.

Design of seat inclination angle

The seat surface needs to be properly reclined so that it can not only facilitate the driver to naturally rest the upper part of the body on the backrest but also reduce the possibility of the hip slipping out from the edge of the seat.

According to the empirical design, 3~5° is the recommended value of the seat inclination angle for B-type vehicles. Therefore, the seat inclination angle of 5° was taken in this paper.

Design of backrest height

The backrest height of the seat of the combine harvester is mainly for the convenience of the driver to check the situation of the grain tank. The height of the seat backrest is determined by the distance from the seat surface to the driver's shoulders. In addition, in order to prevent driver fatigue, the height of the seat backrest should be slightly lower than the driver's sitting shoulder height.

According to [eq. (2)], Table 1, and Table 3, the backrest height Y_4 can be calculated as follows:

$$E(\overline{X_4}) = E\left(\frac{1}{6}\sum_{i=1}^{n} X_i\right) = E\left(\frac{1}{6}\sum_{i=1}^{n}(557 + 598 \ldots + 594)\right) = 577.3\ mm$$

$$Y_4 = 80\%E(\overline{X_4}) + \Delta L_4 = 80\% \times 577.3 + 12 = 473.84\ mm$$

Therefore, the backrest height was set to 470 mm during the design process.

Design of backrest width

In order to make the backrest width of the combine harvester seat meet the widest human body size requirements, the backrest width is designed with the 95th percentile male sitting shoulder width dimension as a reference in this paper.

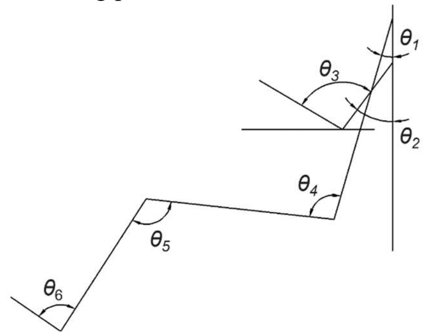
According to Table 1 and Table 3, the backrest width Y_5 can be calculated as follows:

$$Y_5 = Y_{5ma} + \Delta L_5 = 403 + 12 = 415\ mm$$

Considering the shaking of the combine harvester during the working process, the width of the backrest should be appropriately widened. Therefore, the backrest width was set to 420 mm during the design process.

Design of seat backrest inclination

The backrest should have a certain inclination to protect the driver's spine. The joint angles of the driver's comfortable sitting position in the cab are shown in Figure 4.



$$10° < \theta_1 < 20° \quad 15° < \theta_2 < 35° \quad 80° < \theta_3 < 90°$$
$$90° < \theta_4 < 115° \quad 100° < \theta_5 < 120° \quad 85° < \theta_6 < 95°$$

FIGURE 4. Joint angles for a comfortable sitting position.

The angle between the thigh torso and the upper torso of the human body is represented by θ_4. The comfortable angle is between 90° and 115°. Therefore, the seat backrest inclination of 105° was taken in this paper.

Design of steering wheel

The steering wheel is an indispensable driving control device for the combine harvester. Rational design of the steering wheel is directly related to the driver's driving comfort and safety.

Determination of steering wheel spoke shape

B-type cabs mainly have three types of steering wheel spokes: two-spoke, three-spoke, and four-spoke. The three-spoke steering wheel is simple and elegant in appearance, and is convenient for the driver to grasp and flexible in steering. Therefore, the three-spoke steering wheel was selected in this design.

Determination of steering wheel size

When the driver turns the steering wheel, the rotation angle speed and operating torque are determined by the diameter of the steering wheel. The diameter increases with the rotation angle speed and the operating torque decreases. According to anthropometry, taking the width of the elbows of Chinese people in a sitting position as reference, the steering wheel diameter is designed as 400 mm. In order to facilitate the driver to grip the steering wheel, the cross-sectional diameter was set at 30 mm.

Determination of angle between steering wheel and vertical plane

The angle between the steering wheel and the vertical plane is recorded as θ. This angle will affect the force generated when the driver turns the steering wheel. The relationship between the angle and force is shown in Figure 5.

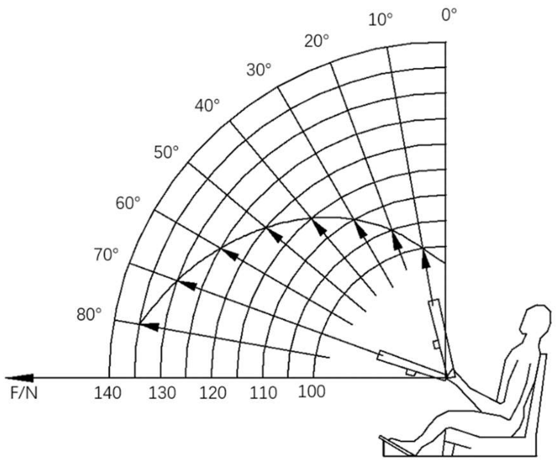


FIGURE 5. Relationship between θ and magnitude of the force.

The greater the angle between the steering wheel and the vertical plane, the greater the force required. However, the smaller the angle θ is, the more unnatural the driver's wrist is, which will easily lead to driver fatigue and affect the driver's driving safety and comfort.

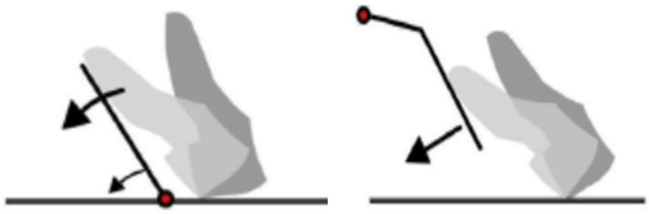
The angle between the steering wheel and the vertical plane is generally between 30° and 75°. The combine harvester is heavy, and the driver needs a large operating force when turning, so the driver is easily fatigued. Therefore, the angle between the steering wheel and the vertical plane is designed to be 60° (Li et al., 2021).

Design of the pedal

The pedal is a driving control device that the driver uses very frequently during driving. A reasonable design of the pedal can allow the driver to have a correct sitting posture and can therefore not only reduce the fatigue of the driver's legs and feet but also relieve the pressure on the upper part of the body.

Determination of the layout of the pedal

There are two types of pedals in the cab: floor type and hanging type, as shown in Figure 6.



(a) Floor type (b) Hanging type

FIGURE 6 Types of foot pedal.

Although a hanging pedal makes it easier for the driver to pedal and saves costs, the driver's calves and feet will be fatigued by long hours of pedal manipulation. In addition, the control accuracy of the hanging pedal is not as good as that of the floor pedal. The combine harvester requires the driver to operate smoothly and with high precision, so as to ensure a clean harvest of grains and a low loss of falling grains. Therefore, the floor type is used for the layout of the pedals designed in this paper.

Design of the pedal plane angle

A reasonable pedal plane angle can make the driver use the pedal lightly, thereby reducing the fatigue of the calves and soles of the feet. The foot pedal angle is calculated according to the empirical equation given in SAE J1516 in this paper (SAE J1516_201110, 2002):

$$\theta = 78.96 - 0.15Z - 0.0173Z^2 \quad (3)$$

where:

θ is the angle between the pedal plane and the horizontal plane, and

Z is the vertical distance from the H point to the AHP point (unit: cm).

According to the coordinates of the H point in the Z direction, Z=49 cm, bringing Z into Equation (3), θ=30.1° can be obtained. Therefore, the pedal plane angle was taken as 30°.

Determination of the pedal shape and size.

Combine drivers are mainly male, so the length and width of the foot pedal are designed by combining the 5th, 50th, and 95th percentile foot length and foot width dimensions of the Chinese adult human body size for males aged 18 to 60.

TABLE 4 Chinese male foot size.

Measurement item	18–60 years old		
	5th percentile	50th percentile	95th percentile
Foot length	230	247	264
Foot width	88	96	103

The foot size of Chinese males is shown in Table 4. Therefore, the designed pedal length is 240 mm and the pedal width is 78 mm. In addition, in order to prevent accidents if the driver's foot slips during operation, a pattern is designed on the pedal surface.

Design of the console

The design of the console mainly includes the design of the manipulation handle and the arrangement of the instrument display. A reasonable console design should ensure that the drivers find it easy to operate. At the same time, it should ensure that they can view the instrument display accurately and quickly while driving.

Design of the manipulation handle

The driver's convenience in applying force and comfort in gripping are the two primary principles in selecting the type of manipulation handle. The shape of the manipulation handle, meanwhile, should be selected in combination with the structure of the human palm. The structure of the human palm is shown in Figure 7. The thenar muscles, hypothenar muscles, and finger muscles are the most muscular parts of the human hand, while the weakest part of the muscle is located in the palm of the hand. In addition, the nerve endings are mostly distributed in the interphalangeal muscles, so the palm of the human hand is more sensitive (Morgan & Carrier, 2013).

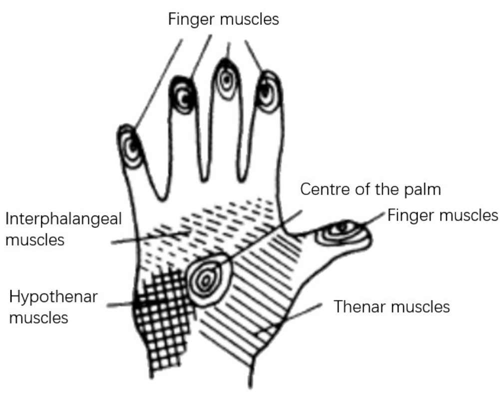


FIGURE 7. Structure of human palm.

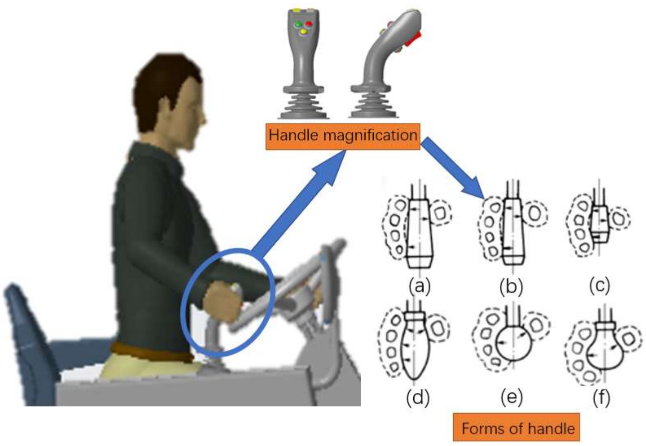


FIGURE 8. Handle magnification and common forms of handle.

The common forms of handle are shown in Figure 8. There is a certain distance between the human palm and the handle in the three types of manipulation handles (a), (b), and (c), which meets the requirements and makes the manipulation more comfortable. The three types of manipulation handles (d), (e), and (f) completely stick to the palm of the hand during manipulation. Although it is more convenient for the driver to grip, long-term use will make the blood circulation of the palm not smooth and cause muscle fatigue, so it is only suitable for the case of less applied force. Therefore, the c-type handle shown in Figure 8(c) was chosen for the manipulation handle in this paper. The Chinese male hand size data is shown in Table 5. The length and the width of the manipulation handle designed in this paper are 110 mm and 50 mm respectively.

TABLE 5. Chinese male hand size.

Measurement item	18–60 years old		
	5th percentile	50th percentile	95th percentile
Hand length	170	183	196
Hand width	76	82	89

The manipulation handle button functions are arranged in a clockwise direction from left to right and top to bottom according to their importance, as shown in Figure 8. The top two buttons are for adjusting the raising and lowering of the header. The middle two buttons from left to right are outward and inward turning button switches for turning the grain box discharge tube. The bottom button is the automatic driving switch. The two buttons on the backside of the handle from top to bottom are the length and height adjustment button switches of the workbench respectively.

Arrangement of the instrument display

The arrangement of the instrument display must follow the following principles:

(a) During driving, the driver can easily and accurately observe the display by using the correct driving posture. At the same time, he/she can manipulate the control buttons of the display.

(b) The layout of the instruments should be reasonable. On the one hand, the instruments should be arranged according to the frequency of use. The more frequently used ones should be placed in a better view position. On the other hand, the instruments arrangement should take into account the visual habits of the human. Therefore, the instruments should be arranged in a clockwise direction from left to right and from top to bottom.

RESULTS AND DISCUSSION

Analysis results of human dimensions of Chinese adults

There are differences between the Chinese human body size and the human body size specified by the Society of Automotive Engineers (SAE). The structural dimensions of the body parts of the 50th percentile for men given by the SAE J833 standard were compared with those of the 50th percentile for Chinese men. The results are shown in Figure 9.

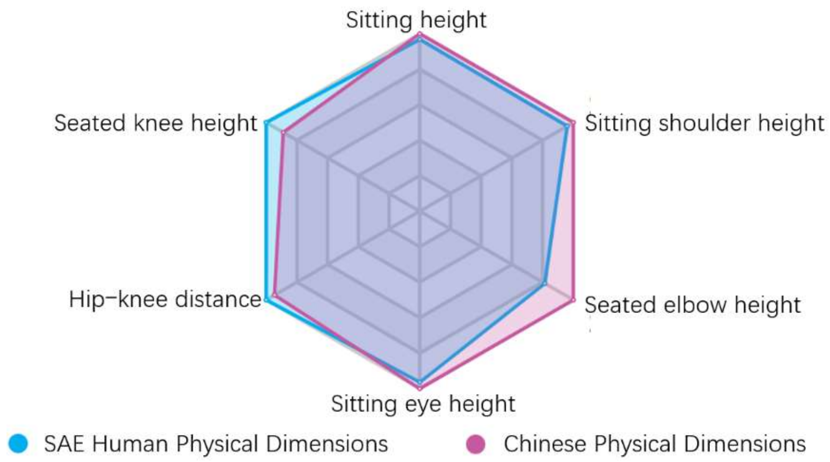


FIGURE 9 Comparison of Chinese body size and SAE body size.

It can be found from Figure 9 that the specific differences between the 50th percentile body part structural dimensions of men given by SAE and the 50th percentile body part structural dimensions of Chinese men are mainly as follows: the sitting height, sitting eye height, sitting shoulder height, seated elbow height and other upper limb dimensions of Chinese men are larger than those prescribed by SAE, while the seated knee height, hip–knee distance and other lower limb dimensions are smaller than those prescribed by SAE.

There are also differences in the body structure dimensions of Chinese men and Chinese women. Therefore, the 50th percentile body structure dimensions of Chinese men and the 50th percentile body structure dimensions of Chinese women were compared. The comparison results are shown in Figure 10.

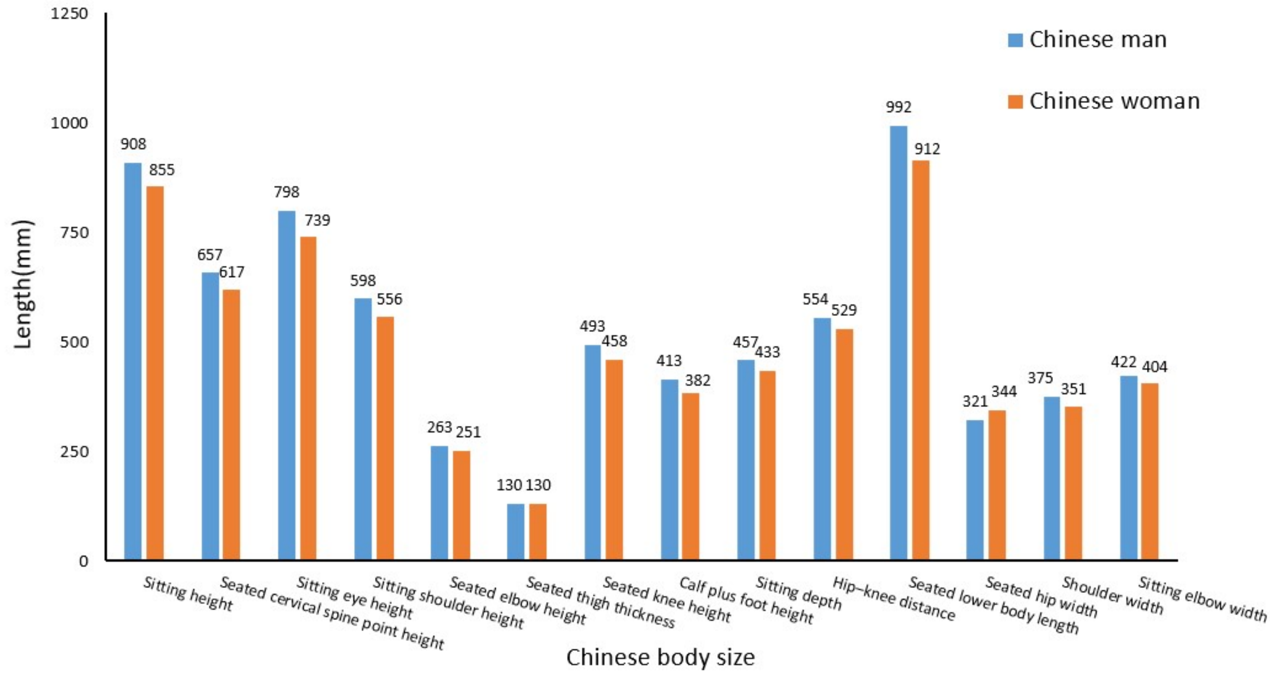


FIGURE 10. Comparison of the 50th percentile body structure dimensions of Chinese men and Chinese women.

It can be found from Figure 10 that all the body structure dimensions of Chinese men are larger than those of Chinese women, except for the seated hip width. Although most drivers of Chinese combine harvesters are male, there are also female combine harvester drivers. Therefore, when designing the size of the cab to suit the Chinese human body size, not only the human body size of the Chinese male driver but also that of the Chinese female driver should be considered to meet the comfort requirements of most drivers of Chinese combine harvesters.

Results of cab structure design

The designed cab seat, steering wheel, foot pedal, and console were modeled in three dimensions using Creo. Their relevant parameters and three-dimensional models are shown in Table 6.

TABLE 6. The relevant parameters and three-dimensional models of each component of the driving control device.

Key components	Parameter	Value	Parameter	Value	3D model
Driving seat	H point coordinates	(680 mm，490 mm)	Front-to-back adjustment	156 mm	
	Seat height	420 mm	Seat depth	410 mm	
	Seat width	430 mm	Seat inclination angle	5°	
	Backrest height	470 mm	Backrest width	420 mm	
	Backrest inclination	105°			
Steering wheel	Spoke shape	Three-spoke	Diameter	400 mm	
	Cross-sectional diameter	30 mm	Angle with vertical plane	60°	
Foot pedal	Type	Floor type	Pedal plane angle	30°	
	Width	78 mm	Length	240 mm	
Console	Manipulation handle	C-type handle	Handle size	110 mm×50 mm	

The driver's manipulation posture in the cab mainly depends on the relative positions of the foot pedals, steering wheel, and seat. Therefore, in this paper, the H-point coordinates are used as a reference for the arrangement of the relative positions in the cab for the main structures that affect human comfort. The corresponding structures and their relative positions are shown in Figure 11.

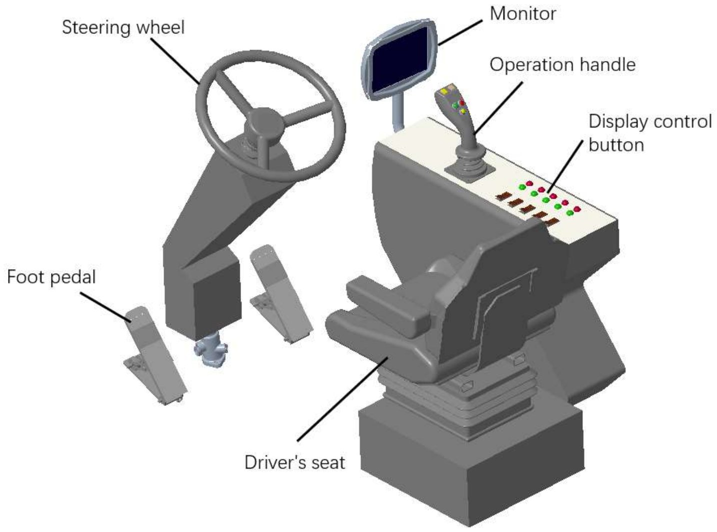


FIGURE 11. Main structures of the cab and their relative positions.

Results of comfort analysis and vision openness analysis

The ergonomics module in Creo can evaluate the comfort level of the driver's arms while driving through the upper limb comfort analysis. Therefore, the 50th percentile human body model for Chinese males was established, as shown in Figure 12.

According to the H point coordinates (680 mm, 490 mm) obtained above, the human body model, the seat, and other components are assembled into the cab. The human body model is controlled to manipulate the steering wheel, as shown in Figure 13. Detailed task parameter settings and comfort results will be displayed on the screen by setting the parameters of the arm manipulating the steering wheel. The results showed that the left arm RULA (Rapid Upper Limb

Assessment) score was 2 points, indicating an acceptable value. However, the right arm RULA score was 3 points, which needed further optimization. For this reason, the initially determined coordinates of point H were adjusted. It was found that the driver's upper limb comfort was improved when the horizontal distance between the H point and the AHP point was 630–655 mm. At this time, the score of the right arm is 1 point, which is acceptable, and the left arm still maintains a score of 2 points, which is within the acceptable range. Therefore, the coordinates of the H point are optimized to be (650 mm, 490 mm) based on the analysis results. In addition, the comfort of operating the handle with the right arm was also analyzed. The human body model was controlled to manipulate the operating handle, as shown in Figure 14. It was found that the right arm RULA score was 2 points when the operating handle was set at 450 mm from the right side of the H point and 260 mm horizontally, which was within the acceptable range.

FIGURE 12. Human standing posture model.

FIGURE 13. Human manipulating steering wheel model.

FIGURE 14. Human manipulating operating handle model.

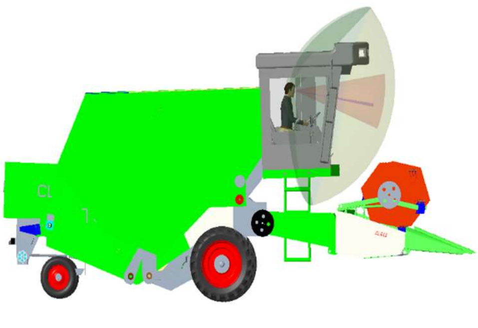
The three main views (direct front view, view of the display, and view of the rearview mirror) of the combine harvester cab design were evaluated. The results are shown in Figure 15. The evaluation results of the three main fields of view of the combine harvester cab are as follows:

(a) The effective field of view directly in front meets the requirements of the visual field evaluation: the effective field of view is within the front glass of the cab, so the road conditions can be observed clearly.

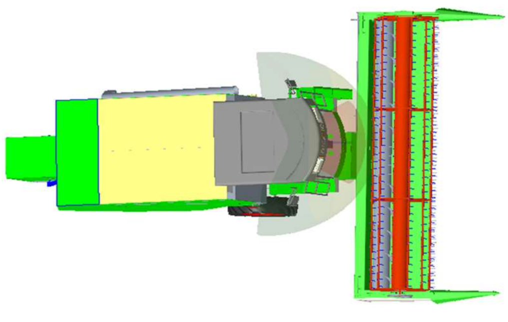
(b) The driver can clearly and completely see the information on the display screen while driving.

(c) The field of the rearview mirror view is within the effective field of vision of the driver. Although part of the effective field of view is interfered with by the frame, the situation in the rearview mirror can still be observed clearly.

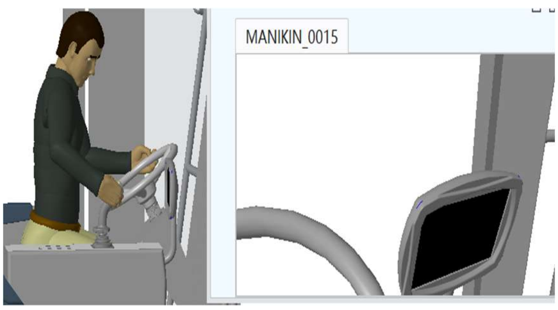
Therefore, the view evaluation of the optimized cab meets the requirements and satisfies the driver's driving safety.



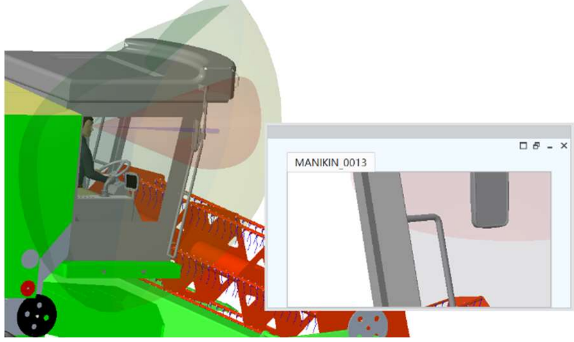
(a) Side view of effective field of view directly in front



(b) Top view of the effective field of view directly in front



(c) View of the display



(d) View of the rearview mirror

FIGURE 15. Results of visual field evaluation.

Correlation analysis between the components frequency and human comfort frequency

The human body will be uncomfortable and nausea, vomiting, and other undesirable phenomena may occur when the resonance frequency is 4 to 8 Hz and 10 to 12 Hz, which will directly affect the operation safety of the combine harvester cab. In addition, the sensitive frequency range of the human lumbar spine is 3 to 6 Hz and 18 to 26 Hz. If the driver is in that frequency range for a long time, he will suffer from muscle aches, numbness in the lower limbs, lumbar spine pain and other diseases. A histogram is drawn based on the main motion parameters and the fundamental frequency of the wheeled wheat combine harvester. It is superimposed with the frequency of human discomfort. The result is shown in Figure 16.

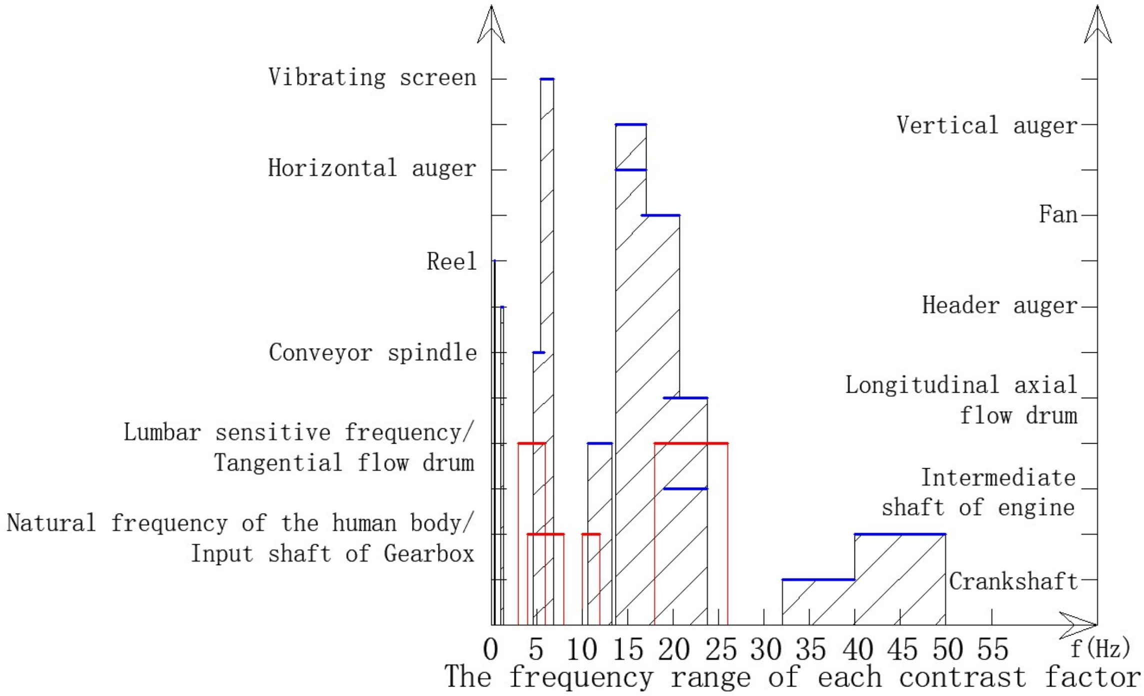


FIGURE 16. Correlation diagram between the working frequency of key components and frequency of human comfort.

As shown in Figure 16, the working frequency range of the conveyor spindle is 4.67 to 5.83 Hz. The working frequency ranges of the vibrating screen and the threshing drum are 5.48–6.85 Hz and 10.67–13.33 Hz respectively. Additionally, the working frequency of the intermediate shaft of the engine is 19 to 23.75 Hz. It is found that the working frequency of the threshing drum easily causes resonance of the human body in the low frequency state, which affects the comfort of the driver in the cab. The working frequency of the intermediate shaft of the engine will cause damage to the human lumbar spine. Furthermore, the working frequency ranges of both the conveyor spindle and vibrating screen overlap with the sensitive frequency range of the human lumbar spine and the natural frequency range of the human body, which has a greater degree of impact on human comfort. Therefore, it is necessary to carry out modal planning for the wheeled wheat combine harvester in the future to better meet the requirements of human comfort.

CONCLUSIONS

(1) The seat, steering wheel, foot pedal, and console are designed with reference to the human body dimensions of Chinese adults in this article. Therefore, the size parameters of the seat, steering wheel, and foot pedal for Chinese people were determined. Additionally, the designed console adopts a c-type handle combined with the structure of the human palm, and its buttons are sorted by importance and frequency of use.

(2) A simulation analysis was conducted to evaluate the comfort level of the Chinese driver's arm based on the ergonomics module in Creo. The results showed that the optimized cab meets the comfort needs of Chinese drivers. In addition, the three main views of the combine harvester cab were evaluated. The results showed that the safety of the driver can be guaranteed during harvesting.

(3) It was found that the working frequency of the conveyor spindle, vibrating screen, threshing drum, and intermediate shaft of the engine in the wheeled combine harvester coincided greatly with the frequency of human discomfort. Therefore, the wheeled wheat combine harvester should be subjected to further modal planning.

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