Comfort evaluation and position parameter optimization of the steering wheel in agricultural machinery based on a three-level evaluation index system

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Abstract: The aim of this study is to evaluate the comfort and optimize the position parameters of steering wheel. Taking the H point of driver as the reference point, three position parameters of steering wheel were determined, which were used as experimental factors. A comprehensive evaluation index system of the comfort was established. The comfort range and optimal levels of three parameters were determined by a single factor test, based on which a response surface optimization and validation test was carried out. The optimization and validation test results show that the expected comprehensive score of the comfort is 0.864, and the average relative error between the predicted and the measured value is 4.18%, indicating that the optimization results are reliable. The findings can provide reference for the comfort optimization design of steering wheel in agricultural devices.

Keywords: agricultural equipment, steering wheel, comfort evaluation, position parameter optimization
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1 Introduction

In the operation of agricultural machinery, bumps frequently occur due to the poor road conditions, which not only reduces the service life of relevant parts, but also causes physical and psychological discomfort of the operators, reducing their work efficiency and even bringing about certain safety hazards[1,2]. At present, the sitting comfort, handling comfort and space comfort of the cab of most agricultural machinery are still far from satisfactory. Steering wheel is an important control device in the cab of agricultural machinery. In the operation process of agricultural machinery, the steering wheel plays certain roles in steering, driving and supporting the hands. In order to control the driving direction, the driver’s hands are put on the steering wheel almost all the time. The spatial position of steering wheel in the cab directly determines the driver's handling difficulty, and then affects the driver's work efficiency and comfort. Therefore, the comfort of the steering wheel to a large extent determines the overall comfort of the cab[3].

In recent years, increasing research has been focused on steering wheel comfort. Yoo et al.[4] measured the acceleration signal transmitted from the steering wheel to the hand through a three-axis translational accelerometer, and correlations were determined between the measured accelerations and the subjective ratings of four expert drivers and ten general drivers by using Stevens’ power law. As a result, the subjective ratings were found to be more highly correlated with the root mean quad (rmq) values than the root mean square (rms) values of the frequency-weighted acceleration. Also, the maximum values of rmq (i.e., the component values in the dominant axis) had the highest correlation with the subjective ratings. Ajovalasit et al.[5] measured the vibration and sound data of the car steering wheel through the SVAN947 portable field analyzer, which has a built-in function that can read sound and vibration stimuli for data analysis of the car steering wheel at idle speed. Cho et al.[6] established a finite element model of the car cockpit including the steering system, and carried out a simulation analysis. By applying force on the steering column and the cab suspension point, the frequency responses of the steering wheel and the floor of the car were calculated. Tagesson et al.[7] proposed a method to measure the complete torque felt by the drive, and tested 17 trucks equipped with steering wheels of three different sizes. The results showed that with decreasing size of the steering wheel, the torque feedback should be reduced. Morioka et al.[8] determined the equivalent comfort of vertical vibration on the hands at three grip forces and two positions by involving 12 subjects, and also determined the absolute threshold value of vibration perception by the two hands in the same frequency range. It was revealed that the shape of the comfort curve is not only closely related to the vibration level, but also affected by the grip strength, indicating that the appropriate

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frequency weight is largely determined by the vibration amplitude and grip strength. In summary, a lot of research has been conducted on steering wheel comfort and certain meaningful results have been obtained. However, the research is mainly focused on the steering wheel of cars, while that on agricultural machinery in which the relative position of the steering wheel is adjustable is relatively limited. In addition, the optimization of steering wheel comfort is mainly carried out from the perspectives of reducing vibration and noise and adjusting the working conditions, while less research attention has been paid to the comfort range of steering wheel position parameters and orthogonal test for optimization design.

Compared with that of other vehicles (such as automobiles), the steering wheel of tractors can generally rotate 1080° (three turns) on one side, which has a much larger range of motion than that of automobile (540°, one and a half turns). In terms of steering wheel layout, because the tractor driver needs to focus the operation at all time and maintain an upright driving posture, the height of the steering wheel relative to the human body is low, and the inclination angle of the steering wheel is smaller than that of automobiles. In addition, tractors are mainly used for field operation with a harsh working environment. When the tractor turns, the torque applied to the steering wheel is generally greater than that of automobiles, accompanied by more obvious vibration of the steering wheel. According to user feedback and market survey, many existing tractors have problems such as inconvenient steering wheel operation and mismatching between the steering wheel and seat layout, which have certain adverse impacts on the driver's handling comfort and operation safety.

For the above reasons, a torque sensor and an angular displacement sensor were used in this study to collect data on a multi-degree-of-freedom agricultural machinery cab test platform, and optimize the position parameters of the steering wheel by establishing a comfort evaluation index system based on the spatial position and dynamic characteristics, with the final aim of improving the comfort of steering wheel in agricultural machinery. The results may provide a theoretical basis and data support for the design, manufacture and optimization of agricultural machinery steering wheel.

2 Materials and methods

2.1 Test instrument and equipment

The test equipment used in this research is a multi-degree-of-freedom agricultural machinery cab test platform developed by our research group. The space position of the seat, steering wheel, pedal and control lever can be adjusted (Figure 1). Figure 2 and Table 1 show the schematic side view of the main operating devices of the cab test platform and the operating range of the main components. The adjustment ranges of the main components of the driving platform are in line with the ISO 4253 standards. The instruments and equipment used in the test mainly include a JNNT-S-20N·m torque sensor, a GTCA3636 angular displacement sensor and a USB-2611 data acquisition card as shown in Figure 3.

2.2 Selection of the test factors and levels

In ergonomics, the hip point between the torso and thigh is referred to as the H point, which is often used as a reference point for the layout design of the cab[9]. In this study, the H point (hip point) was used as a reference point, and three position parameters were selected for the steering wheel, including the inclination angle of the steering wheel (β), the front-back distance (l) and up-down height (h) between the steering wheel center (W point) and H point as shown in Figure 4.

Figure 1 Agricultural machinery cab test platform

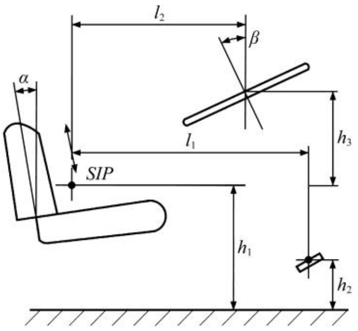
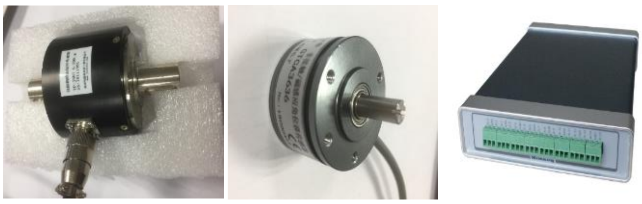


Figure 2 Main parameters of test platform

Table 1 Adjustment ranges of main components of the test platform

Parameter	Range
α: Seat back inclination angle/(°)	5-15
β: Tilt angle of steering wheel/(°)	10-50
l_1: Horizontal distance between SIP and center point of pedal/mm	600-720
l_2: Horizontal distance between SIP and steering wheel/mm	380-525
h_1: Height of seating index point (SIP)/mm	450-550
h_2: Height of center point of pedal/mm	120
h_3: Vertical distance between SIP and steering wheel/mm	260-385



a. Torque sensor b. Angle sensor c. Data acquisition card

Figure 3 Instruments and equipment used in the test

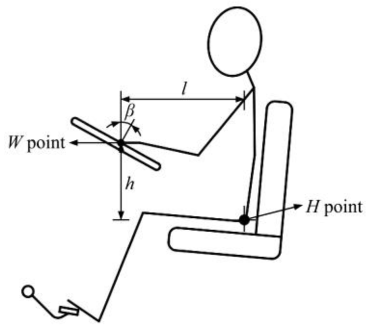


Figure 4 Schematic diagram of steering wheel

According to the adjustment range of the steering wheel, five levels were selected for each factor (Table 2). The factor level parameters of the steering wheel were set in line with the ISO 4253 standard. Moreover, we referred to the steering wheel layout parameters of various tractor models to finally determine the factor level setting of the steering wheel.

Table 2 Different levels of factors for the evaluation of steering wheel comfort

Level	Factors		
	Steering wheel inclination β/(°)	Front-back distance l /mm	Up-down height h /mm
1	10	380	260
2	20	415	290
3	30	450	320
4	40	485	350
5	50	520	380

2.3 Test method and process

In this study, 10 male drivers (with a certain driving age, 24-34 years old, 60-70 kg in weight, and 168-173 cm in height) were invited for the steering wheel comfort test at 14:00-17:00 in the afternoon. The body size of the drivers was measured with the indicators presented in Table 3. Before the test, a torque sensor and an angular displacement sensor were installed on the steering wheel, and the steering wheel was adjusted to the level position of each factor. After the operator's sitting posture was stable, holding the steering wheel. The five joint angles of θ, ε, γ, φ and ω in Figure 5 were measured by a digital display angle ruler, respectively. After the angle test was completed, the steering wheel was first turned 90° clockwise, then 180° counterclockwise, and then 90° clockwise to return to the initial position. The data of steering wheel torque and angular displacement were recorded with time. The test was repeated three times at each factor level. The analog signals collected by the sensor can be output as digital signals through the acquisition card and saved to the computer software for subsequent data analysis and processing.

Table 3 Basic information of the test personnel

Measurement	Mean value/mm
Upper arm length	316
Forearm length	240
Sitting height	928
Shoulder height when sitting	601
Hand width	83
Hand length	186

2.4 Test design

2.4.1 Single factor test

(1) Influence of inclination angle on the handling comfort

Taking the H-point as the reference point, the front-back distance l was adjusted to 415 mm, and the up-down height h was adjusted to 290 mm. Then, the single factor test was carried out at the inclination angle β of 10°, 20°, 30°, 40° and 50°, respectively. The index values of sitting and handling comfort were measured and calculated respectively, and the average value of three repeated tests was calculated.

(2) Influence of front-back distance on the steering wheel comfort

Taking the H-point as the reference point, the inclination angle β was first adjusted to 30°, and the up-down height h to 290 mm. Then, the single factor test was conducted with the front-back distance l being set at 380, 415, 450, 485 and 520 mm, respectively. The index values of sitting and handling comfort were measured and calculated respectively, and the average value of three repeated tests was calculated.

(3) Influence of up-down height on the steering wheel comfort

Taking the H-point as the reference point, the inclination angle β was first adjusted to 30°, and the front-back distance l to 415 mm. Then, the single factor test was carried out under at the up-down height h of 260, 290, 320, 350 and 380 mm, respectively. The index values of sitting and handling comfort were measured and calculated respectively, and the average value of three repeated tests was calculated.

2.4.2 Response surface optimization test

Based on the single factor test results, BBD (Box Behnken design) was used to optimize the three variables, including the inclination angle A, front-back distance B and up-down height C. The response surface test of three factors at three levels was carried out, and then the comprehensive comfort score of combination of position parameters at each factor level was calculated, which was taken as the response value in the response surface test. Table 4 shows the factor-level coding for the steering wheel response surface test.

Table 4 Factor-level coding for steering wheel response surface test

Level	Factor		
	A: Steering wheel inclination angle/(°)	B: Front-back distance/mm	C: Up-down height/mm
–1	20	380	260
0	30	415	290
1	40	450	320

The response surface test was used to calculate the optimal solution of the combinations of different levels of the three position parameters. Combined with human factors engineering theory, the influence of the interaction on steering wheel comfort was analyzed, and the position parameters of steering wheel were optimized.

2.5 Construction of the comfort evaluation index system

To make the evaluation indices representative, definite, sensitive and independent[10], a three-level comfort evaluation index system was built by taking into account of both sitting comfort and handling comfort. Among them, the indices of sitting comfort were the angles of the main human body joints under the driving posture, and those of handling comfort were selected in accordance with relevant literature. The specific indices are listed in Table 5.

Table 5 Comfort evaluation indices

First-level indices	Second-level indices	Third-level indices
Comprehensive score	Sitting comfort	① Angle between arm and trunk (θ)
		② Angle between thigh and trunk (ε)
		③ Angle between thigh and calf (γ)
		④ Angle between calf and the foot sole plane (φ)
		⑤ Angle between upper arm and forearm (ω)
	Handling comfort	① Average torque $\bar{M}$
		② Maximum torque M_{max}
		③ Linearity G_L
		④ Change rate of average torque $\bar{v}$
		⑤ Average torque-rotation stiffness $\bar{\mu}$
		⑥ Impulse H
		⑦ Power W
		⑧ Number of outliers Ne

2.5.1 Evaluation indices of the sitting comfort

As shown in Figure 5, the angle between arm and trunk (θ), between thigh and trunk (ε), between thigh and calf (γ), between calf and the foot sole plane (φ), and between upper arm and forearm (ω) were selected to measure the sitting comfort in this study.

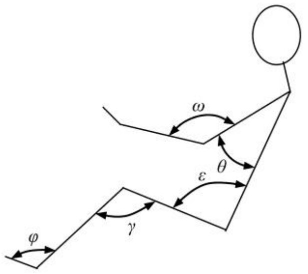


Figure 5 Human joint angles in driving posture

As shown in Table 6, there are some discrepancies in the results on the optimal comfort range of each joint angle of the human body in different research. In order to better determine the optimal comfort range of each joint angle, the comfort range was appropriately reduced: the maximum value of the left limit value and the minimum value of the right limit value in all comfort ranges of the same joint angle were used as the left and right limit values of the new comfort range, respectively, which was used to evaluate the sitting comfort.

Table 6 Human joint angle ranges in comfortable driving posture (°)

Angle	Rebiffe[11]	Grandjean[12]	Porter[13]	Park[14]	Shijian Luo[15]	New range
θ	10-45	20-40	16-74	7-37	5-28	20-28
ε	95-120	100-120	89-112	100-131	99-115	100-112
γ	95-135	110-130	103-136	120-152	111-134	120-130
φ	90-110	90-110	81-105	82-124	89-124	90-105
ω	80-120	80-120	80-161	86-144	80-129	86-120

2.5.2 Evaluation indices of the handling comfort

(1) Average torque $\bar{M}$

In this study, the average torque is defined as the arithmetic mean value of all torques in the process of the operator turning the steering wheel anticlockwise for half a cycle and then turning it clockwise for half a cycle:

$$\bar{M} = \frac{M_1 + M_2 + \cdots M_n}{n} \tag{1}$$

where, M_1, M_2,..., M_n represent each measurement result of the steering wheel torque during the test process, N·m; $\bar{M}$ is the average torque during the process of steering wheel operation, N·m; n is the number of collected steering wheel torques.

(2) Maximum torque $M_{\max}$

If any torque is M_i (i=1,2,…,n) when the operator controls the steering wheel, the maximum torque is defined as $M_{\max}$ (N·m):

$$M_{\max} = maxM_i (i = 1, 2, ..., n) \tag{2}$$

(3) Linearity G_L

In the process of steering wheel operation, a good linear relationship between the torque and angle is conducive to the perception of the real-time position of the steering wheel, which will contribute to more accurate and comfortable handling of the steering wheel[16]. Therefore, the nonlinear error between torque and angle is defined as linearity:

$$G_L = \frac{\max\{|M_i - k\alpha_i + b|\}}{k\alpha_{\max} - \alpha_{\min}} \ (i = 1, 2, \ldots, n) \tag{3}$$

$$k = \frac{n\sum M_i\alpha_i - \sum M_i \sum \alpha_i}{n\sum \alpha_i^2 - (\sum \alpha_i)^2} \tag{4}$$

$$b = \frac{\sum \alpha_i^2 \sum M_i - \sum \alpha_i \sum M_i\alpha_i}{n\sum \alpha_i^2 - (\sum \alpha_i)^2} \tag{5}$$

where, k and b are the slope and intercept of the first-order fitting equation between the torque and rotation angle; M_i is any torque during operation; α_i is the corresponding angle of the steering wheel; $\alpha_{\max}$ and $\alpha_{\min}$ are the maximum and minimum angle, respectively.

(4) Change rate of average torque $\bar{v}$

In the process of steering wheel operation, a greater change rate of torque with time will lead to poorer steering wheel handling comfort[17]. Therefore, in this study, the absolute value of torque change rate in the whole process was calculated and averaged, and defined as the average torque change rate:

$$\bar{v} = \frac{\sum |v_i|}{n} (i = 1, 2, \ldots, n) \tag{6}$$

$$v_i = \frac{M_{i+1} - M_i}{t_{i+1} - t_i} (i = 1, 2, \ldots, n-1) \tag{7}$$

where, v_i is the change rate of torque with time, N·m/s.

(5) Average torque-rotation stiffness $\bar{\mu}$

After the synchronous collection of the data of torque and angle, the relationship of torque changing with rotation angle can be analyzed. Greater stiffness of torque with the angle will lead to poorer handling comfort of the steering wheel[18]. Therefore, in this study, the arithmetic mean of the absolute value of torque stiffness with rotation angle in the whole process was calculated, and defined as average torque-rotation stiffness:

$$\bar{\mu} = \frac{\sum |\mu_i|}{n} (i = 1, 2, \ldots, n) \tag{8}$$

$$\mu_i = \frac{M_{i+1} - M_i}{\alpha_{i+1} - \alpha_i} (i = 1, 2, \ldots, n-1) \tag{9}$$

where, μ_i represents the stiffness of torque varying with the rotation angle, N·m/rad.

(6) Impulse H

In the process of steering wheel operation, a higher accumulation of torque with time will more likely cause fatigue of the driver. Therefore, the impulsive moment was introduced as an index for evaluating the handling comfort of steering wheel in this study[19]:

$$H = \int_{t_a}^{t_b} M(t) \mathrm{d}t \tag{10}$$

where, H is the impulse, kg·m^2/s; t_a and t_b are the starting and ending time points of the operation process, and $M(t)$ is a function of torque M with respect to time t during the study.

(7) Power W

During the operation of the steering wheel, resistance is overcome to do work, that is the accumulation of torque M on the angle α. In addition, the magnitude of work can reflect the weight of load. The more work is done, the poorer the handling comfort will be[20]. Therefore, work is introduced as an index in the handling comfort evaluation of steering wheel:

$$W = \int_{\alpha_a}^{\alpha_b} M(\alpha) \mathrm{d}\alpha \tag{11}$$

where, W is the power during the operation of the steering wheel, J; α_a and α_b are the initial and final angular displacement of the operation process, respectively; and $M(\alpha)$ is a function of torque M at the rotation angle α during the study.

(8) Number of outliers Ne

Torque and angle will vary with time in the process of steering wheel operation. According to the Grubbs criterion, this study performed a discriminant analysis on all torque samples, and calculated the allowable minimum torque $M_{t(\min)}$ and $M_{\alpha(\min)}$ and maximum torque $M_{t(\max)}$ and $M_{\alpha(\max)}$ in the torque-time and torque-rotation data. The torque that does not satisfy either $M_{t(\min)}$

$\leq M_t \leq M_{t(\max)}$ or $M_{\alpha(\min)} \leq M_i \leq M_{\alpha(\max)}$ was defined as an outlier. A larger number of outliers indicates poorer handling comfort. Therefore, the expression of the number of steering wheel outliers *Ne* is defined as:

$$N_e = f(M_t, M_\alpha) \tag{12}$$

2.5.3 Calculation of the comprehensive comfort score

(1) Sitting comfort score

In the experimental factors, the original value of *j* evaluation index at *i* level was recorded as x_{ij}, and the comfort membership degree can be obtained by data standardization:

$$y_{ij} = \begin{cases} 1 - \dfrac{\delta_1 - x_{ij}}{\delta_2 - x_{ij}} & x_{ij} < \delta_1 \\ 1 & \delta_1 \leq x_{ij} \leq \delta_2 \\ 1 - \dfrac{x_{ij} - \delta_2}{x_{ij} - \delta_1} & x_{ij} > \delta_2 \end{cases} \tag{13}$$

where, δ_1 and δ_2 are the left and right end points of the optimal comfort range of the *j* joint angle index, and the optimal comfort range [δ_1, δ_2] is the new range listed in Table 6. The membership degrees of the five sitting comfort indices at each test level were combined into a matrix to be evaluated, which was subjected to dimensionality reduction by principal component analysis. Finally, the sitting comfort score *Sc* for each level was obtained through normalization.

(2) Handling comfort score

Since the eight evaluation indices are all inverse indices, that is, a higher index value represents poorer comfort, Equation (14) was used to calculate the membership degrees of the evaluation indices:

$$y_{ij} = \frac{(x_{ij})_{\max} - x_{ij}}{(x_{ij})_{\max} - (x_{ij})_{\min}} \tag{14}$$

where, $(x_{ij})_{\min}$ and $(x_{ij})_{\max}$ are the minimum and maximum values of the *j* index at the *i* level. The membership degrees of the eight indices at each test level were combined into a matrix to be evaluated, which was then subjected to dimensionality reduction by principal component analysis, and finally, normalization was performed to obtain the handling comfort score H_c at various levels.

(3) Comprehensive comfort score

In an evaluation system, reasonable weighting is of great significance to the accuracy of the evaluation results[21]. The methods of weighting include subjective and objective weighting, among which subjective weighting mainly depends on expert scoring to determine the weight coefficient, including Delphi[22] and AHP method[23]. Objective weighting mainly determines the weights according to calculation rules, such as the variation coefficient method[24] and the entropy weight method[25]. Among them, the variation coefficient method can comprehensively evaluate the sitting and handling comfort, which is more accurate and reasonable. Therefore, in this study, the variation coefficient method was selected for weighting in the experimental optimization, and then the comprehensive comfort score *Cc* of each level was obtained, namely:

$$C_c = \omega_1 S_c + \omega_2 H_c \tag{15}$$

where, C_c, S_c and H_c are the scores of comprehensive comfort, sitting comfort and handling comfort, respectively; ω_1 and ω_2 are the weights of sitting comfort and handling comfort.

3 Results

3.1 Results of the single factor test

3.1.1 Influence of inclination angle on the steering wheel comfort

Table 7 presents the comfort scores of the steering wheel at different levels of inclination angle, based on which the relationship curve of the comfort score with the changes of the inclination angle β can be drawn (Figure 6).

Table 7 Comfort scores of the steering wheel at different levels of inclination angle

Inclination angle β /(°)	Sitting comfort	Handling comfort	Comprehensive comfort
10	0.14	0.00	0.08
20	0.28	0.82	0.52
30	0.80	0.83	0.81
40	0.91	0.41	0.69
50	0.16	0.56	0.34

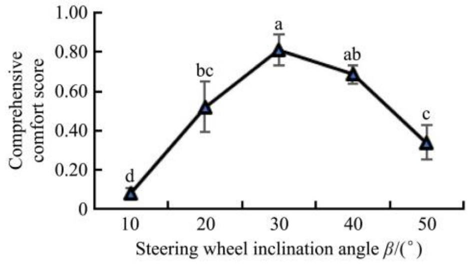


Figure 6 Influence of the inclination angle on the comfort of steering wheel

Figure 6 shows that with increasing values of β, the comprehensive comfort scores of steering wheel first increases and then decreases, and reaches the maximum value when β is 30°. The main reason is that when β is small, the axis of the driver's wrist is almost parallel to the ground. At this time, the wrist joint has a large degree of bending, and the high internal tension is not conducive to the application of force, resulting in low comprehensive comfort scores[26]. When β is gradually increased to 20°, the driver's wrist is gradually relaxed, and the relaxation of the upper arm and forearm is more flexible, which improves the comprehensive comfort. However, when β exceeds 40°, the wrist joint is tightened again, which is not conducive for the driver to apply torque to the steering wheel, making it more difficult to rotate the steering wheel in the horizontal direction, which will reduce the comprehensive comfort. To sum up, from the perspective of comprehensive comfort of steering wheel, the optimal value of β is 30° and the optimal value range is 20°-40°.

3.1.2 Influence of front-back distance on the steering wheel comfort

Figure 7 shows the relationship curve of the comprehensive score of steering wheel comfort with the changes of front-back distance *l*. The results show that with the increase of *l*, the comprehensive comfort score of the steering wheel also firstly increases and then decreases, and reaches the maximum value at the *l* value of 415 mm. The main reasons are as follows. At a low *l* value, the driver's upper body is close to the steering wheel, with both hands being tightly pressed against the steering wheel, resulting in large pressure load; at the same time, the angle between the upper arm and forearm is small, and the elbow joint is tightened inward, which is not conducive for the driver to apply torque on the steering wheel. These factors together lead to poor comprehensive comfort of the steering wheel. When the *l* gradually increases to 380 mm, the upper arm and forearm will be gradually relaxed, and the relaxation becomes more flexible, which is conducive to the control of the driver over the steering wheel, so the comprehensive comfort is improved. However, when *l* exceeds 450 mm, the arm, forearm and wrist are almost spatially collinear, which is easy to cause fatigue to the arm; in addition, when the hand reaches the far end of the steering wheel, the upper body will be forced to lean forward, which will cause an increase in the component load of trunk gravity and correspondingly a reduction of the comprehensive comfort[27]. To sum up, considering the comprehensive comfort of the steering wheel, the optimal level of l is 415 mm, and the optimal range is 380-450 mm.

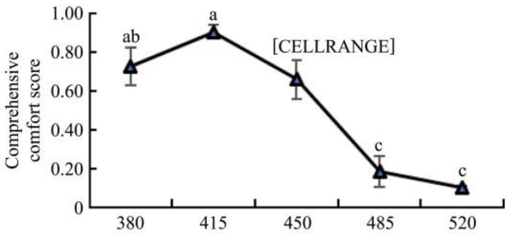


Figure 7 Effect of front-back distance on steering wheel comfort

3.1.3 Influence of up-down height on the steering wheel comfort

Figure 8 shows the relationship curve of the comprehensive score of steering wheel comfort with the changes of up-down height h. It can be found that with the increase of h, the comprehensive comfort score of steering wheel first increases and then decreases as well, and finally tends to a lower level without significant changes, reaching the maximum value when h is 290 mm. The main reasons are as follows. At a low value of h, the driver's hands are placed at a low position and there is a large angle between the upper arm and forearm, making the elbow joint to bear more load of the arm gravity; in addition, when the hand reaches the far end of the steering wheel, there will be a higher pressure between the palm and the steering wheel. These factors together cause poor comprehensive comfort of the steering wheel. When h gradually increases, it is more convenient for the driver to overcome the arm gravity by relying on the steering wheel; at the same time, the distance between the steering wheel and the driver is appropriately reduced, which contributes to more flexible control of the driver over the steering wheel and correspondingly improvement of the comprehensive comfort. However, when h exceeds 320 mm, the angle between the upper arm and forearm decreases, and that between the arm and the trunk increases, with the whole arm in a state of lifting up, which easily leads to more fatigue to the shoulder joint and a decrease in elbow joint flexibility, resulting in poor comprehensive comfort of the steering wheel[28]. To sum up, in terms of comprehensive comfort of the steering wheel, the optimal level of h is 290 mm, and the optimal range is 260-320 mm.

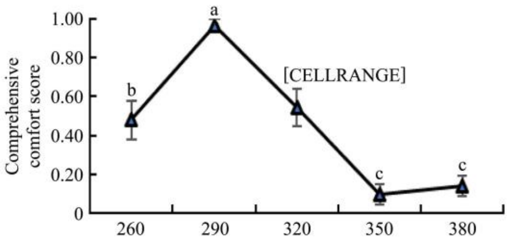


Figure 8 Effect of up-down height on steering wheel comfort

3.2 Response surface optimization results

3.2.1 Test results

Table 8 presents the factor-level combinations for the steering wheel response surface test and the response values. It can be found that there are obvious differences in comprehensive comfort score under different combinations of position parameters. In order to optimize the position parameters, the response surface test is used to establish a regression model for evaluating the steering wheel comfort.

Table 8 Factor-level combinations for the steering wheel response surface test

Test number	A: Inclination angle/(°)	B: Front-back distance /mm	C: Up-down height/mm	Y: Comprehensive comfort
1	0	0	0	0.8581
2	0	0	0	0.8017
3	0	1	-1	0.4584
4	1	0	1	0.3396
5	0	-1	-1	0.5125
6	-1	1	0	0.3189
7	-1	0	1	0.4122
8	0	-1	1	0.6424
9	1	0	-1	0.5305
10	-1	-1	0	0.3038
11	1	-1	0	0.7088
12	0	0	0	0.8793
13	1	1	0	0.2804
14	0	0	0	0.9066
15	0	1	1	0.1757
16	-1	0	-1	0.3018
17	0	0	0	0.7209

3.2.2 Establishment of a regression model for comfort evaluation of the steering wheel

As shown in Table 9, a linear model, a two-factor interactive model, and a second-order model are used to fit the test data. The p-value of the misfit term of the second-order model is 0.7205, which has the lowest significance, indicating the best fitting effect. In the second-order model, $R^2_{\mathrm{Adj}}=0.9267$ and $R^2_{\mathrm{Pre}}=0.8297$, which are both close to 1, and the difference between them is within 0.2, indicating that the model can be used for accurate fitting of the steering wheel comfort.

Table 9 Fitting results of steering wheel comfort under different regression models

Model type	Linearity	2FI	Second-order
R^2_{Adj}	–0.0293	–0.1383	0.9267
R^2_{Pre}	–0.2698	–0.6566	0.8297
p-value of misfit term	0.0093	0.0064	0.7205

Table 10 shows the results of variance analysis of the steering wheel comfort with the second-order model. It can be found that factor C and AC have no significant effect on the comfort of steering wheel ($\alpha=0.05$). Therefore, the insignificant factors C and AC should be eliminated and the regression model should be re-fitted. Table 11 shows the variance analysis results of steering wheel comfort with the modified second-order regression model, and the p-value is 0.0001, indicating that the modified second-order model has a better fitting effect. In addition, the coefficient of determination R^2 of the modified model is 0.9358, which is greater than 0.8, indicating a good agreement of the fitting function with the experimental data.

The fitting function between the revised steering wheel comfort comprehensive score and each factor is:

$$\begin{aligned} Y = & -31.18 + 0.29A + 0.14B - 3.17*10^{-4}AB + 1.54*10^{-5}BC \\ & -2.51*10^{-3}A^2 - 1.63*10^{-4}B^2 - 1.30*10^{-5}C^2 \end{aligned} \tag{16}$$

where, Y is the comprehensive score of steering wheel comfort; A is the inclination angle of the steering wheel surface, (°); B is the front-back distance; mm; C is the up-down height, mm.

Figures 9 and 10 show the comparison between the predicted and measured values of steering wheel comfort and the residual distribution of regression model. It can be observed that the predicted values and the measured values are almost on the same straight line, indicating small errors between the predicted and measured values and a high prediction accuracy of the regression model. In addition, the residuals are almost distributed on the same straight line as well as with small errors from the expected values and normal distribution, which again confirms the reliability of the fitting function in the regression model. Therefore, Equation (16) can be used to predict the steering wheel comfort under the combination of different inclination angles, front-back distances, and up-down heights.

Table 10 Variance analysis of steering wheel comfort of second-order regression model

Variation source	Square sum	Freedom	Mean square	F-value	p-value	Significance
Model	0.89	9	0.099	23.49	0.0002	**
A	0.034	1	0.034	8.14	0.0246	*
B	0.11	1	0.11	26.00	0.0014	**
C	0.0068	1	0.0068	1.62	0.2435	N
AB	0.049	1	0.049	11.72	0.0111	*
AC	0.023	1	0.023	5.41	0.0529	N
BC	0.043	1	0.043	10.14	0.0154	*
A^2	0.24	1	0.24	58.19	0.0001	**
B^2	0.15	1	0.15	36.06	0.0005	**
C^2	0.16	1	0.16	38.76	0.0004	**
Residual	0.029	7	0.0042			
Misfitting term	0.0076	3	0.0025	0.47	0.7205	N
Pure error	0.022	4	0.0054			
Total	0.92	16				

Note: * indicates significant influence (p<0.05); ** indicates extremely significant influence (p<0.01).

Table 11 Variance analysis of modified second-order regression model for steering wheel comfort

Variation source	Square sum	Freedom	Mean square	F-value	p-value	Significance
Model	0.86	7	0.12	18.73	0.0001	**
A	0.034	1	0.034	5.22	0.0482	*
B	0.11	1	0.11	16.68	0.0027	**
AB	0.049	1	0.049	7.52	0.0228	*
BC	0.043	1	0.043	6.51	0.0312	*
A^2	0.24	1	0.24	37.32	0.0002	**
B^2	0.15	1	0.15	23.13	0.0010	**
C^2	0.16	1	0.16	24.86	0.0008	**
Residual	0.059	9	0.0065			
Misfit term	0.037	5	0.0074	1.37	0.3923	N
Pure error	0.022	4	0.0054			
Total	0.92	16				

Note: * indicates significant influence (p<0.05); ** indicates extremely significant influence (p<0.01).

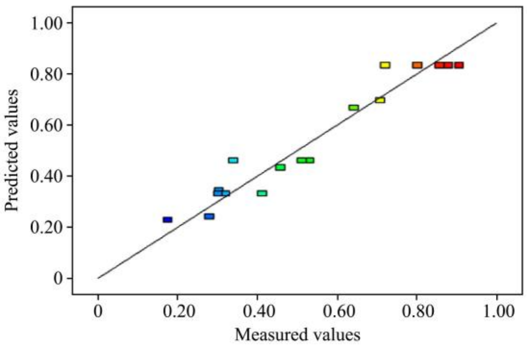


Figure 9 Comparison of predicted and measured values

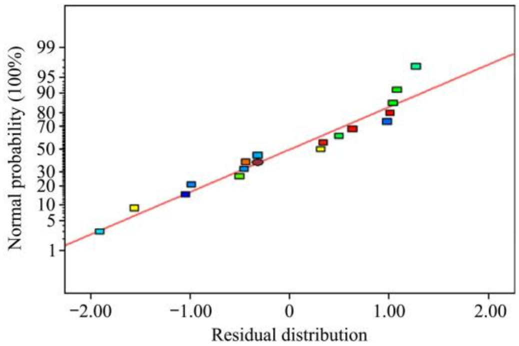


Figure 10 Residual distribution

3.2.3 Analysis of the influence of test factors on the comfort

According to the F value of each factor in Table 10, the influence of each factor on steering wheel comfort follows the descending order of B (front-back distance), A (inclination angle), C (up-down height). In addition, according to Table 11, the AB and BC interactions show significant influence on steering wheel comfort. Hence, it is necessary to analyze the influence of interaction among different factors on steering wheel comfort.

1) Interaction between A (inclination angle) and B (front-back distance) on steering wheel comfort

Figure 11 shows the response surface plot of the interaction between A (inclination angle) and B (front-back distance). It can be observed that there is a peak value in the comprehensive comfort score, indicating that the design range of BBD (Box Behnken design) is more accurate. The contour plot of AB interaction is shown in Figure 12. It can be seen that when the inclination angle of the steering wheel is less than 25°, the comfort score of the steering wheel is average, ranging from 0.4 to 0.7 at any front-back distance. When inclination angle is between 25° and 40° and the front-back distance is only 380-420 mm, the comfort score of the steering wheel is high (about 0.8-1.0). The main reasons are as follows. In the BBD design scope of steering wheel, when the inclination angle of the steering wheel is small or the front-back distance is large, the driver is far away from the steering wheel, which is easy to force the upper body to lean forward and not conducive to the application of torque, resulting in poor comfort of the steering wheel; when the inclination angle of the steering wheel is moderate or large and the front-back distance is small, the driver can control the steering wheel closely and rely on the steering wheel to overcome the gravity of both hands so as to easily and efficiently control the steering wheel, resulting in high handling comfort of the steering wheel[29]. Therefore, in order to improve the comfort of the steering wheel, the inclination angle of the steering wheel should be adjusted to 25°-40° and the front-back distance should be adjusted to 380-420 mm.

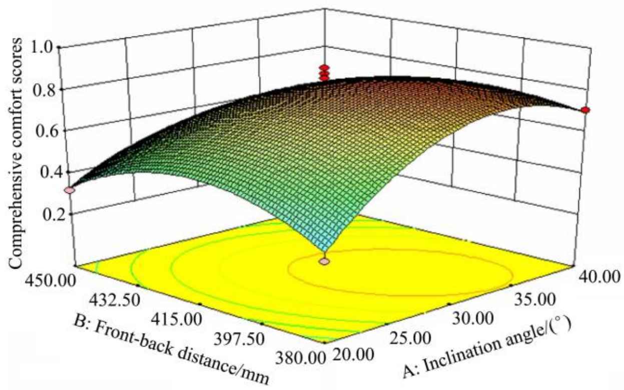


Figure 11 Response surface plot of AB interaction

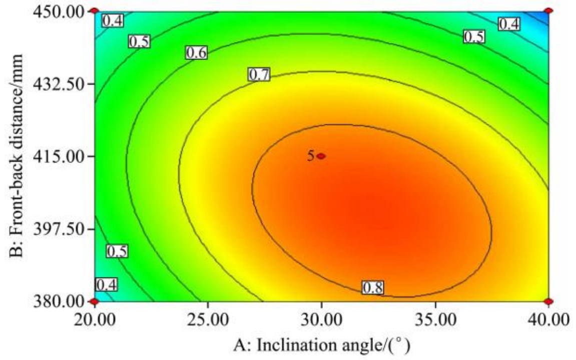


Figure 12 Contour graph of AB interaction

2) Interaction between *B* (front-back distance) and *C* (up-down height) on steering wheel comfort

Figure 13 shows the response surface plot of the interaction between *B* (front-back distance) and *C* (up-down height). It is observed that there is a peak value in the comprehensive comfort score of the steering wheel, indicating that the design range of BBD is more accurate.

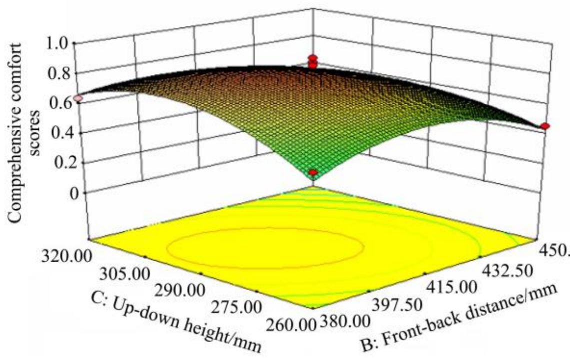


Figure 13 Response surface plot of BC interaction

The contour plot of *BC* interaction is shown in Figure 14. When the front-back distance is greater than 430 mm, the comfort score of the steering wheel is average, ranging from 0.4 to 0.7 at any up-down height. When the front-back distance is 385-420 mm, the up-down height is 275-310 mm, and the comfort score of steering wheel is high (about 0.8-1.0). The main reasons are as follows. In the BBD design range of steering wheel, when the front-back distance is large, or the up-down height is too high or too small, the angle between the driver's upper arm and forearm is large, which leads to an increase in the required torque and general handling comfort; when the front-back distance is moderate or small, and the up-down height is moderate, the driver is close to the steering wheel, and the forearm is almost parallel to the steering wheel surface, which is conducive to the application of torque to the steering wheel with high efficiency and good comfort[30].

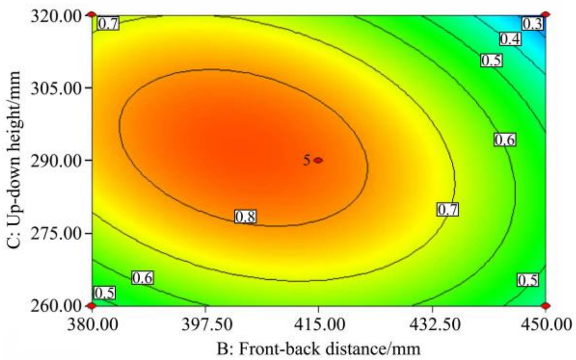


Figure 14 Contour graph of BC interaction

Therefore, to improve the comfort of the steering wheel, the front-back distance should be adjusted to 385-420 mm, and the up-down height should be adjusted to 275-310 mm.

3.3 Optimization and verification test of the position parameters

According to the second-order regression model of steering wheel, the three position parameters of steering wheel are optimized for higher comfort, and the optimization results are verified by experiments. In Design-Expert 8.0 software, the range of steering wheel inclination angle (*A*) is set as 20°-40°, the range of front-back distance (*B*) as 380-450 mm and the range of up-down height (*C*) as 260-320 mm. Through response surface optimization analysis, it can be found that the optimal combination of steering wheel position parameters is as follows: $A = 32.29°$, $B = 400.85$ mm, and $C = 293.18$ mm. With these combination position parameters, the comprehensive score of steering wheel comfort is expected to be as high as 0.864.

In order to verify the reliability of the optimization results of the position parameters, based on the agricultural machinery cab test platform, the steering wheel inclination angle is adjusted to 32°, the front-back distance to 401 mm, and the up-down height to 293 mm. Three validation tests were repeated, and the results are listed in Table 12. The average relative error between the predicted and measured values is 4.18%, implying the reliability of the optimization results of the position parameters.

Table 12 Verification test results on the optimization of the position parameters

No.	Comprehensive comfort scores		Relative error
	Predicted values	Measured values	
1	0.864	0.932	7.30%
2	0.864	0.851	1.53%
3	0.864	0.833	3.72%
Average	0.864	0.872	4.18%

4 Conclusions

The aim of this study is to evaluate the steering wheel comfort of agricultural machinery and optimize the position parameters. Firstly, by taking H-point as the reference point, three experimental factors, including the steering wheel inclination angle, the front-back distance, and the up-down height were selected. Five sitting comfort indices and eight handling comfort indices were extracted, and then the comfort range and optimal levels of the three position parameters were determined by single factor test. On this basis, response surface optimization design was carried out for the three position parameters of steering wheel. Combined with variance analysis, the second-order regression model was established and modified. Through variance analysis of the model, the interaction between the steering wheel inclination angle and front-back distance and that between the front-back distance and up-down height were all significant ($\alpha = 0.05$). Based on the F values, the contributions of the three position parameters were ranked. According to the comfort scores of the steering wheel, the mechanism underlying the influence of the position parameters on the comfort of the steering wheel was analyzed. Finally, the optimization and validation test were carried out. The results show that the comprehensive score of the steering wheel comfort is expected to be 0.864, and the average relative error is 4.18% from the measured value. The optimization results of the steering wheel position parameters are reliable, and the findings can provide certain reference for the comfort optimization design of agricultural machinery steering wheel. This study only proposes the comfort evaluation index system for agricultural machinery steering wheel from the perspective of ergonomics, and puts forward corresponding improvement suggestions, but there is still a lack of research on the impact mechanism of environmental factors on the comfort. The follow-up research can start with the human-machine-environment coupling relationship, and introduce environmental factors such as road excitation and driving speed to better understand the impact mechanism on agricultural machinery comfort. In addition, the comfort evaluation model and position parameter optimization design of agricultural machinery cab can be further improved.

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