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Quantitative Evaluation of Vehicle Seat Driving Comfort During Short and Long Term Driving

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ABSTRACT Regarding changes of subjective and objective parameters of comfort during short and long-term driving, the arbitrariness of traditional subjective evaluation methods, as well as the defects of objective method where issues can be qualitatively but not quantitatively analyzed. By measuring pressure distribution and electromyography during short and long-term driving respectively, the article obtained pressure indicators, electromyography characteristic parameters and the corresponding subjective evaluations of drivers. The variation of subjective and objective parameters of comfort, the difference in terms of comfort and the fatigable body parts were tested. By means of correlation analysis completed the indicators screen. Proposed a new comprehensive weighting method-AHP to limit entropy method, established the mapping relations between subjective comfort and objective indicators, which based on pressure distribution and physiological information during short-term and long-term driving. Obtained a quantitative evaluation method that applies pressure distribution, physiological information and subjective evaluation to effectively evaluate driving comfort, and thus provided a theoretical basis for evaluating driving comfort.

INDEX TERMS Comfort, long-term driving, quantitative assessment, short-term driving.

I. INTRODUCTION

As a long contact part with the driver, car seat is the key to improve driving experience, and ease the fatigue. Human comfort is an overall feeling, each driver has his own subjective evaluation and definition of comfort, with various influence factors. In addition, driving comfort is the comprehensive composite of feelings from different body parts. Thigh, buttock and back as the main parts in contact with the seat, the pressure distribution between driver-seat and the support of the seat to those parts were major influencing factors of driving comfort. Each of these should be provided by the driver's seat and can be described in terms of driver-seat interface pressure.

As the ergonomics research goes on, the unreasonable pressure distribution between driver-seat, resulting in poor blood circulation and muscles fatigue, therefore the driving comfort was reduced. So researchers have begun to focus on the human-machine intervention and assessment methods, that uses pressure change to effectively assess the driving (dis)comfort. Ming and Qunsheng [1] studied the correlation between the objective evaluation and subjective evaluation of the seat comfort, and 8 indicators to characterize pressure distribution were put forward. Giuseppe *et al.* [2] showed that pressure patterns are the most important reference for the seat design. Porter *et al.* [3] used pressure distribution to predict discomfort in road trial. Hartung *et al.* [4] tested the intra-individual and inter-individual variations through divided the pressure distribution into buttock, thigh and back. Akgunduz *et al.* [5] found that there is a strong correlation between maximum and average pressure of cushion and perceived comfort. About the correlational research on pressure distribution and comfort, De Looze *et al.* [6] stated that pressure distribution appears to be the objective measure with the most clear association with the subjective ratings. Na *et al.* [7] tested the relationship between dynamic pressure indicators and discomfort. Kyung and Nussbaum [8] studied the associations between subjective ratings, driver-seat interface pressure and pressure level, results indicated that driver-seat interface pressure was more related with comfort ratings.

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Zenk *et al.* [9] reported an objective assessment approach of optimal load distribution from the pressure on the seat and the discomfort felt by the person sitting. Marenzi *et al.* [10] designed a novel interface pressure measurement system, then can continuous testing the pressure distribution of the seated people. Naddeo *et al.* [11] studied the significance of pressure at interface to (dis)comfort perception, the results showed that pressure distribution can affect perceived physiological and tactile (dis)comfort. In addition, researchers (Kamijo *et al.*, Oudenhuijzen *et al.*, Kolich *et al.*, Dunk *et al.*) [12]–[15] assessed the pressure levels among body parts, as well as between anthropometric groups, investigated the correlation between pressure distribution and driving (dis)comfort [16].

In order to improve the driving comfort, while providing support to human body, the vehicle seat needs to be able to ease the fatigue during long-term driving. Regarding the research of short and long-term driving, Reed *et al.* [17] conducted a short-term session and a 3h driving simulation experiment, investigated the factors affecting driving discomfort. Helander and Lijian [18] found that as driving duration increases, the discomfort increases, as well as the fatigue of human body. Gyi *et al.* [19] stated that at least 2h duration of test can clearly assess discomfort, that is fatigue. Uenishi *et al.* [20] through one-hour driving simulation, discovered that the increase of discomfort was related to fatigue. Grujicic *et al.* [21] used musculoskeletal modeling and simulation methods studied the factors that cause of long-term driving fatigue. Sharma and Bindele [22] proposed an alternative approach for fatigue detection, that can reduce the accidents that caused by fatigue of drivers. Stork *et al.* [23] proposed a new method for appropriate prediction of drowsy driving through the detection of various approaches for driver fatigue. Kim [24] performed a subjective evaluation of sitting posture stability after 2 hours highway driving, showing that long-term driving makes the posture prone to shift, the driving comfort decrease, whereas fatigue increase. Hongchang *et al.* [25] found that using the unconstrained heartbeat signal can describe the driving psychological fatigue, which extracted through pressure sensor array. Main methods employed for the researches above are subjective evaluation and electromyography. Since ISO 11228 Ergonomics promulgated in 2007, the ergonomics and (dis)comfort has been the main task of the research, the difference between short-term and long-term driving comfort are still at the stage of exploration and study.

Although the above studies have well revealed the correlation among pressure distribution, short-term & long-term driving and comfort, there are the following problems: 1) Driving comfort is a comprehensive perception, it can not systemically quantify overall driving comfort with only pressure distribution to evaluate driving comfort; 2) There are many body pressure indicators, it is not yet clear the correlation between pressure indicators and comfort, the selected parameters might be extreme or inaccurate; 3) The difference between short-term and long-term driving comfort, and the fatigue parts not clear; 4) The quantitative mapping relations between subjective comfort and objective indicators of vehicle seat based on pressure distribution and physiological information have not been established yet, and lack scientific evaluation method that uses pressure distribution and physiological information to evaluate the driving comfort.

Aiming at the issues hereinbefore, based on the pressure distribution, physiological information indicators and subjective comfort, the paper applied research on driving comfort and quantitative evaluation method for comfort of vehicle seat during short and long term driving. Firstly, studied the difference between pressure distribution and physiological information during short-term and long-term driving. Secondly, applying correlation analysis to test the correlation between pressure indicators and comfort. At last, established an ontology model for the driving comfort, putting forward a new comprehensive weighting method-AHP to limit entropy method, and set up the comfort quantitative evaluation method, which is based on the pressure distribution, physiological information and comfort during short-term and long-term driving.

TABLE 1. The basic information about testees.

Testee	Height (cm)	Weight (kg)	Driving experience (year)
No. 1 testee	167	61	6
No. 2 testee	167	60	9
No. 3 testee	167	59	8
No. 4 testee	168	59	10
No. 5 testee	178	75	7
No. 6 testee	177	78	9
No. 7 testee	178	68	5
No. 8 testee	179	76	4
No. 9 testee	177	72	8
No. 10 testee	176	70	6
No. 11 testee	177	75	6
No. 12 testee	179	70	5
No. 13 testee	176	75	7
No. 14 testee	177	70	9
No. 15 testee	179	78	17
No. 16 testee	177	74	6

II. METHODS

A. OVERVIEW OF EXPERIMENT AND PARTICIPANTS

According to the Human Dimensions of Chinese Adults GB10000-88, and the analysis report about the human dimensions of Chinese adults made by China National Institute of Standardization in 2009 [26], as in Table 1, six 50th and ten 95th were selected from the recruiters. Referring to PRC Road Traffic Law on State Security, drivers who drive vehicles on highways during the internship period shall be accompanied by drivers who hold corresponding or higher driving licenses for more than three years. Due to the test route of objective test is round trip expressway from downtown to the airport with total duration of 2.5 hours, to ensure drivers security, and to enhance the rationality and scientificity of test, then chooses the samples with more than 3 years of driving experience, all of the testees were healthy, with no history of family disease. In the test, the SUV vehicle' driver seat was tested for the pressure distribution, electromyography and subjective comfort at different durations on the road at the average speed of 50km/h.

The subjective evaluation is with SAE-score system, lower the score is, poorer the comfort is, and vice versa. According to SAE-score system, 1 score representing unbearable, 10 score representing very comfortable, and the score between 1 and 10 representing a continuum of comfort state. The evaluation includes the comfort after 15min driving and the comfort after 90min driving, as shown in Table 2. According to Road Traffic Safety Law, to avoid fatigue driving, the driver should have a rest after 240min driving, then to guarantee the safety of drivers, the continuous driving should be less than 240min. In addition, Reed *et al.* [27] stated that 15min is considered sufficient for drivers to 'settle' in car seats. Reed *et al.* [28] and Kari *et al.* [29] found that 70% of American drivers less than 50 miles per day, 82% of human' trips take less than 20min. As indicated in Schmidt *et al.* [30], 30min duration is necessary to study the long term posture of humans in vehicles. According to the above research, the subjective evaluation of comfort was performed after 15min and 90min, respectively, and testees answered every question on the subjective sitting comfort evaluation table.

TABLE 2. **The subjective evaluation form.**

Evaluation indicators	Comfort (10-point scale)
Driving comfort after 15min driving	1, 2, 3, 4, 5, 6, 7, 8, 9, 10
Driving comfort after 90min driving	1, 2, 3, 4, 5, 6, 7, 8, 9, 10

The objective test in this article mainly includes pressure test and electromyography detection, test route is round trip from downtown to the airport with total duration of 2.5 hours. When testing pressure distribution, laid the pressure map on the seat surface, and the map must be flat and well pressed, meanwhile fixed them to the seat with masking tape and ropes. Then the personal information such as height and weight were recorded. Finally, the testees adjusted the vehicle seat to a comfortable driving posture, then test the pressure distribution between human and seat surface during different driving duration with Tekscan pressure measurement system. When testing electromyography, firstly, all tested muscles were performed maximum voluntary contraction (MVC) prior to testing electromyography, to obtain the maximum electromyography signal of each muscle. Next, to avoid interference of vehicle noise on electromyography signal, the vehicle was turned off after 15min and 90min driving, respectively, then applying biopac physiological recorder test the electromyography signal of muscles. As shown in Fig. 1.

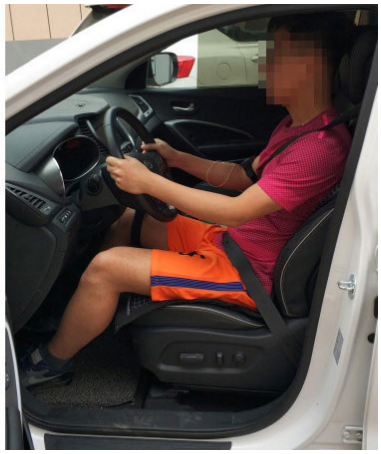

FIGURE 1. **The objective experiment.**

B. DATA ANALYSIS

1) OBJECTIVE DATA ANALYSIS

According to human body division from human anatomy, and the researches by Yun *et al.* [31], De Looze *et al.* [6], Na *et al.* [7], Zenk *et al.* [32], Naddeo *et al.* [11], showed that different body parts in contact with the seat all play important roles in determining overall comfort, and the comfort was closely related to the pressure on the buttock, thigh and back. The pressure nephogram measured during 15min and 90min driving, respectively, were divided into buttock, thigh and back, as shown in Fig. 2. A total of 12 pressure variables were derived (Table 3): (1) the first 3 variables indicated average contact pressure; (2) the second 3 variables were related to average contact area; (3) the third 3 variables were cared about maximum contact pressure; (4) the last 3 variables described average contact force.

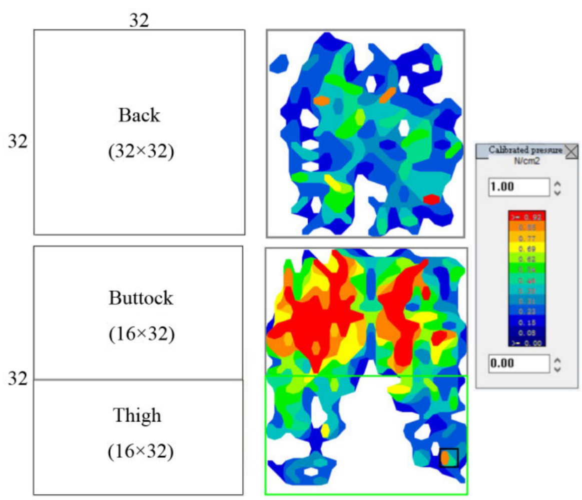

FIGURE 2. **Division of two pressure mats for three local body parts.**

Mechanical characteristic of human muscles are measured by muscle activity. The muscle activity is defined as the ratio

TABLE 3. Pressure variables and groups.

Group	Variable name and description	
Average contact pressure	avgBT	Buttock
	avgTH	Thigh
	avgB	Back
Average contact area	aBT	Buttock
	aTH	Thigh
	aB	Back
Maximum contact pressure	maxBT	Buttock
	maxTH	Thigh
	maxB	Back
Average contact force	FBT	Buttock
	FTH	Thigh
	FB	Back

of muscle stress divided by the muscle strength, reflecting the muscle utilizing proportion when the external force acts. When the muscle activity is 0, it indicates that the muscle has not yet been used. When the muscle activity is 1, it is shows that the muscle is completely exhausted. When the muscle activity is higher than 1, it is manifests that the muscle exceeds the limit, and the muscle may be strained, the muscle tissue broken down. Through measuring the muscle activity of musculus triceps brachii, trapezius, erector spinae, gluteus maximus, rectus femoris, and gastrocnemius muscle, as shown in Table 4, then studied the muscle stress characteristics in different duration.

TABLE 4. Muscle activity variables and groups.

Group	Variable name and description
Arm	The muscle activity of musculus triceps brachii
Shoulder	The muscle activity of trapezius
Back	The muscle activity of erector spinae
Buttock	The muscle activity of gluteus maximus
Thigh	The muscle activity of rectus femoris
Calf	The muscle activity of gastrocnemius

2) CORRELATION ANALYSIS

Based on the 12 pressure indicators and corresponding subjective comfort, which tested during 15min and 90min driving in road trials, the correlation analysis between pressure indicators and subjective comfort was analyzed by statistic method [33], [34] and SPSS software. The paper performed a significant test of the correlation by two-tailed test, when significance level $\alpha = 0.05$, the two-tailed test for a given significance level becomes sig. If sig $< \alpha$, there was significant correlation between variables. If correlation coefficient r $\leq$ 0.2, there was uncorrelated basically between variables. If correlation coefficient 0.3 $\leq$ r $<$ 0.5, there was moderate correlation between variables. If correlation coefficient 0.5 $\leq$ r, there was strong correlation between variables.

3) QUANTITATIVE EVALUATION METHOD FOR COMFORT OF VEHICLE SEAT

Driving comfort is "an evaluation of subjective satisfaction from both physiology and psychology aspects for drivers" [35]. The AHP [36]–[41] is a hierarchial method presents the qualitative results about subjective judgements in quantitative terms, that proposed by satty[38] in 1985. The entropy method [42], [43] based on the factors' variation to calculate the factors' objective weights. According to the above weighting methods, a new comprehensive weighting method-AHP to limit entropy method was put forward, which is based on the pressure distribution, physiological information and corresponding subjective comfort, that is, AHP method is adopted to modify entropy weights one by one. Established the mapping relations between pressure distribution, physiological information and subjective comfort, proposed a quantitative evaluation method about the driving comfort. The calculation procedures as follows:

(1) Calculating the comfort indicators' weights with AHP method. Based on the correlation results among pressure distribution, physiological information and subjective evaluation during short-term and long-term driving, find out the evaluation indicators. The influence of those indicators on subjective driving comfort is performed by using the scale of 1-9 measurement system.

Construct the pairwise comparison matrix, calculate the maximum eigenvalue and corresponding eigenvector. Through consistency check, then calculate the comfort indicators' weights in terms of driving comfort about every driver.

$$W = \begin{bmatrix} w_{11} & \cdots & w_{1n} \\ \vdots & \ddots & \vdots \\ w_{m1} & \cdots & w_{mn} \end{bmatrix} \tag{1}$$

According to equation (2), as well as the number of experts and the corresponding elimination ratio as shown in Table 5, eliminate the weight outliers that deviate from the other drivers' opinions about the driving comfort.

$$d_i = \sum_{j=1}^{m} d_{ij} \tag{2}$$

In the equation (2), $d_i = 1 - \sqrt{\frac{1}{n}\sum_{k=1}^{n}\left(w_{ik} - w_{jk}\right)^2}(i, j = 1, 2 \cdots m)$, representing the similarity sum of the weights according to the results of the i-th driver' opinion and the weights according to the results of the other drivers' opinions about driving comfort. The larger value of d_i, indicating the smaller deviation, and vice versa.

Calculate the average of weight matrix columns $W_j^1 (j = 1, 2 \cdots n)$, then obtain the weights of comfort indicators.

TABLE 5. The number of experts and the corresponding elimination ratio.

The number of experts	5	6	7	8	9	10
The number of eliminated experts by using clustering analysis	1	1-2	1-2	2	2-3	2-3
The number of experts whose results were adopted	4	4-5	5-6	6	6-7	7-8

(2) Based on the objective pressure indicators and muscle activity indexes from the road trail, applying entropy method to calculate the objective weight of comfort indicators, that is W_j^2.

Using equation (3) to standardize the comfort evaluation indexes.

$$b_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - x_{min}} \tag{3}$$

In the equation (3), x_{max} and x_{min} representing the most optimum and inappropriate value of the same indicators belong to different evaluation unit, respectively.

According to the equation (4) and (5), bringing the above result data into equation (6), then calculate the weights of those indicators.

$$H_j = -\frac{1}{lnp}\left(\sum_{i=1}^{p} f_{ij} ln f_{ij}\right) \quad (i = 1, 2 \cdots p, j = 1, 2 \cdots n) \tag{4}$$

$$f_{ij} = \frac{b_{ij} + 1}{\sum_{i=1}^{p}(b_{ij} + 1)} \tag{5}$$

$$w_j^2 = \frac{1 - H_j}{n - \sum_{j=1}^{n} H_j} \quad (j = 1, 2 \cdots n) \tag{6}$$

(3) Using the marginal value of comfort indicators that calculate by AHP to revise the weights of indexes that test by entropy method. Extract the marginal value from the above weights of factors that calculate by AHP, one of them is the minimum value-a, and the other is the maximum value-b.

If $W_j^2 < a$, then let $W_j = a$. Applying equation (7) to redistribute the fractional variation of weights.

$$W_k^{2*} = \left(W_j^2 - a\right) \frac{W_k^2}{\sum_{i=j+1}^{n} W_i^2} + W_k^2 \quad (k = j+1, j+2 \ldots n) \tag{7}$$

If $W_j^2 \in [a, b]$, then let $W_j = W_j^2$.

If $W_j^2 > b$, then let $W_j = b$. Using equation (8) to redistribute the fractional variation of weights to other indicators.

$$W_k^{2*} = \left(W_j^2 - b\right) \frac{W_k^2}{\sum_{i=j+1}^{n} W_i^2} + W_k^2 \quad (k = j+1, j+2 \ldots n) \tag{8}$$

Based on above procedures, the weights of driving indicators are revised one by one, then get the revised weights of comfort indicators. If there is still cases where $W_n^{2*} \notin [a, b]$, applying the equation (9) or equation (10) to redistribute the fractional variation of weights to other indicators, until all the comfort indicators' weights meet the requirements.

$$W_k^{2*} = \left(W_j^2 - a\right) \frac{W_k^2}{\sum_{i=1}^{n} W_i^2 - W_j^2} + W_k^2 \quad (1 \le k \le n, \text{ and } k \ne j) \tag{9}$$

or

$$W_k^{2*} = \left(W_j^2 - b\right) \frac{W_k^2}{\sum_{i=1}^{n} W_i^2 - W_j^2} + W_k^2 \quad (1 \le k \le n, \text{ and } k \ne j) \tag{10}$$

In conclusion, based on the analysis results of AHP and entropy method, using the weights measured by AHP to modify the weights tested by entropy method. It can eliminate the deficiency of entropy method's vulnerability to extremum, and by combining the pressure distribution, physiologic information and subjective evaluation, analyzed the comfort from both physiology and psychology aspects, then more scientifically and effectively established a new quantitative evaluation method for comfort of vehicle seat, which combined subjective evaluations and objective datum.

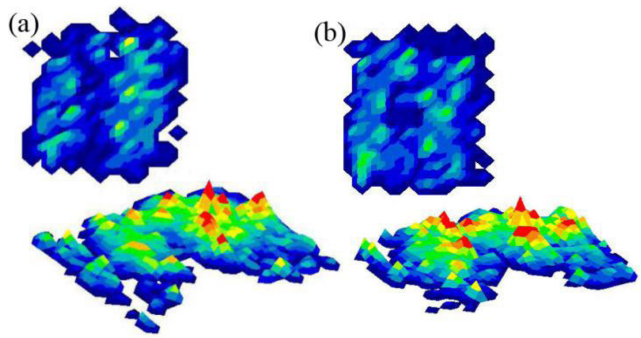

FIGURE 3. Pressure distribution.

III. RESULTS

A. THE PRESSURE DISTRIBUTION DURING SHORT-TERM AND LONG-TERM DRIVING

Driving comfort is a perception of pressure and load acts directly on human body [11]. When driving in a comfortable posture, the pressure patterns from the road trial during 15min and 90min driving, as shown in Fig. 3. The pressure distribution between driver-seat cushion and driver-seat backrest is gradually decreased around the ischial tuberosity, waist and back, respectively, then the results of pressure distributions correspond to the human biomechanics. The percentage of load in buttock and thigh is that the buttock account for approximately 52.95%-73.07%, the thigh account for approximately 26.93-47.05%, as in Fig. 4. Comparing the pressure distribution, as shown in Fig. 3, the average contact pressure of buttock tested when driving for 90min is larger than the

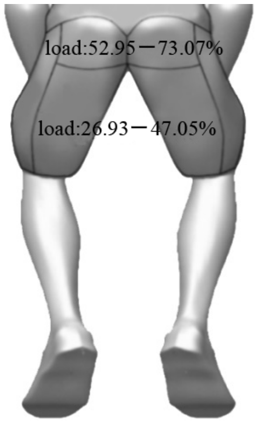

FIGURE 4. Load distribution of body parts in contact with the vehicle seat.

results of 15min, the contact area of backrest is increased, and the corresponding average contact pressure is decreased.

In order to quantify the pressure variations during short-term and long-term driving, comparison between the results of 12 pressure indicators that tested during 15min and 90min driving in road trials, as shown in Fig. 5 (Since the trends in pressure indicators were identical, and the data quantity was too much, the article analyzed one testee's data as an example). Combined with the rate change of pressure indicators, as shown in Fig. 6, and contrasted the pressure indicators tested during short-term driving with the results measured during long-term driving. Then compared the pressure indicators-average contact pressure in thigh and back that tested during 90min driving with the results measured during 15min decreased, and the average contact pressure in the buttock increased. The reason is that the contact areas between buttock-seat, thigh-seat and back-seat increased, as well as the contact force, whereas the rate change of the contact force of buttock is higher than the rate change of contact area, for thigh and back, the reverse is true. Then the average contact pressure of buttock that tested after 90min driving duration is larger than the results of 15min, the average contact pressure of thigh and back decreased. In addition, the maximum contact pressure is the maximum of all pressure points, with the increase of driving duration, the irritating effect on the human body increased.

Table 6 is the correlation results between pressure indicators and comfort, after 15min and 90min driving, respectively. As shown in Table 6, the coefficients of correlation between subjective ratings and average contact pressure of buttock, average contact pressure of thigh and average contact pressure of back which measured after 15min and 90min driving are higher than 0.5, and have strong correlation with comfort. The coefficients of correlation between subjective ratings and average contact force of buttock, average contact force of thigh and average contact force of back between 0.593 and 0.658, then there was strong correlations between subjective ratings and the average contact force (15min: $\rho = 0.612$, $p < 0.05$; $\rho = 0.593$, $p < 0.05$; $\rho = 0.603$, $p < 0.05$; 90min: $\rho = 0.643$, $p < 0.01$; $\rho = 0.596$, $p < 0.05$; $\rho = 0.658$, $p < 0.01$). In conclusion, the impact of pressure indicators on driving comfort are ultimately reflected in average contact pressure and average contact force between driver-seat interface.

B. THE MUSCLE ACTIVITY AND MUSCLE MECHANICAL CHARACTERISTICS DURING SHORT-TERM AND LONG-TERM DRIVING

Analyzed from human biomechanics, the human motion control is the mechanical response of major muscle group, which controlled coordinately by muscles from different body parts. The fatigue level varies with the duration of driving, so is the comfort level. Hence, the article carries out muscle activity and muscle mechanical characteristics analysis in different driving duration, as shown in Fig. 7.

Study the muscles activity of human body after 15min and 90min driving, as shown in Fig. 7, the result shows that under driving posture, the muscle activity of rectus femoris is the largest of all, the muscles activity of musculus triceps brachii and gastrocnemius muscle are relatively higher than the muscles activity of musculus triceps brachii and gluteus maximus. After long-term driving, the muscles rate change of rectus femoris, trapezius and gastrocnemius muscle are higher than the rest. Therefore, the muscle utilizing proportion and the rate of change of rectus femoris, trapezius and gastrocnemius muscle are relatively higher. Finally, it proves that thigh, upper limb and calf are prone to fatigue than shoulder, back and buttock when driving in long-term road.

C. SYNTHETIC WEIGHTS

The comfort factors' weights that tested by the above evaluation method during short-term and long-term driving are listed in Table 7 and Table 8, A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8, A_9 represents the weight of average contact pressure of buttock, average contact force of buttock, average contact pressure of thigh, average contact force of thigh, average contact pressure of back, average contact force of back, the muscle activity of rectus femoris, the muscle activity of musculus triceps brachii and the muscle activity of gastrocnemius muscle on comfort, respectively. When measuring the subjective weights with AHP, in order to enhance the rationality and scientificity of the weights, the driving experience of testees were more than 3 years, no disease, and with decent work history. Through clustering analysis eliminate the weights of three outliers-experts' test results, then obtained the weights of the comfort indicators during 15min and 90min driving duration, as shown in Table 7 and Table 8. The objective weights as shown in Table 7 and Table 8, were measured by entropy method, that combining the evaluation results with objective data, quantified the driving comfort of vehicle seat.

As shown in Tables 7 and 8, the results of comfort indicators that tested during 15min and 90min driving, both showed that muscle activity of human body has a greater weight than pressure indicators on comfort, however, there are also some differences between the influence of those indicators on comfort. The results showed that effects of indicators' weights

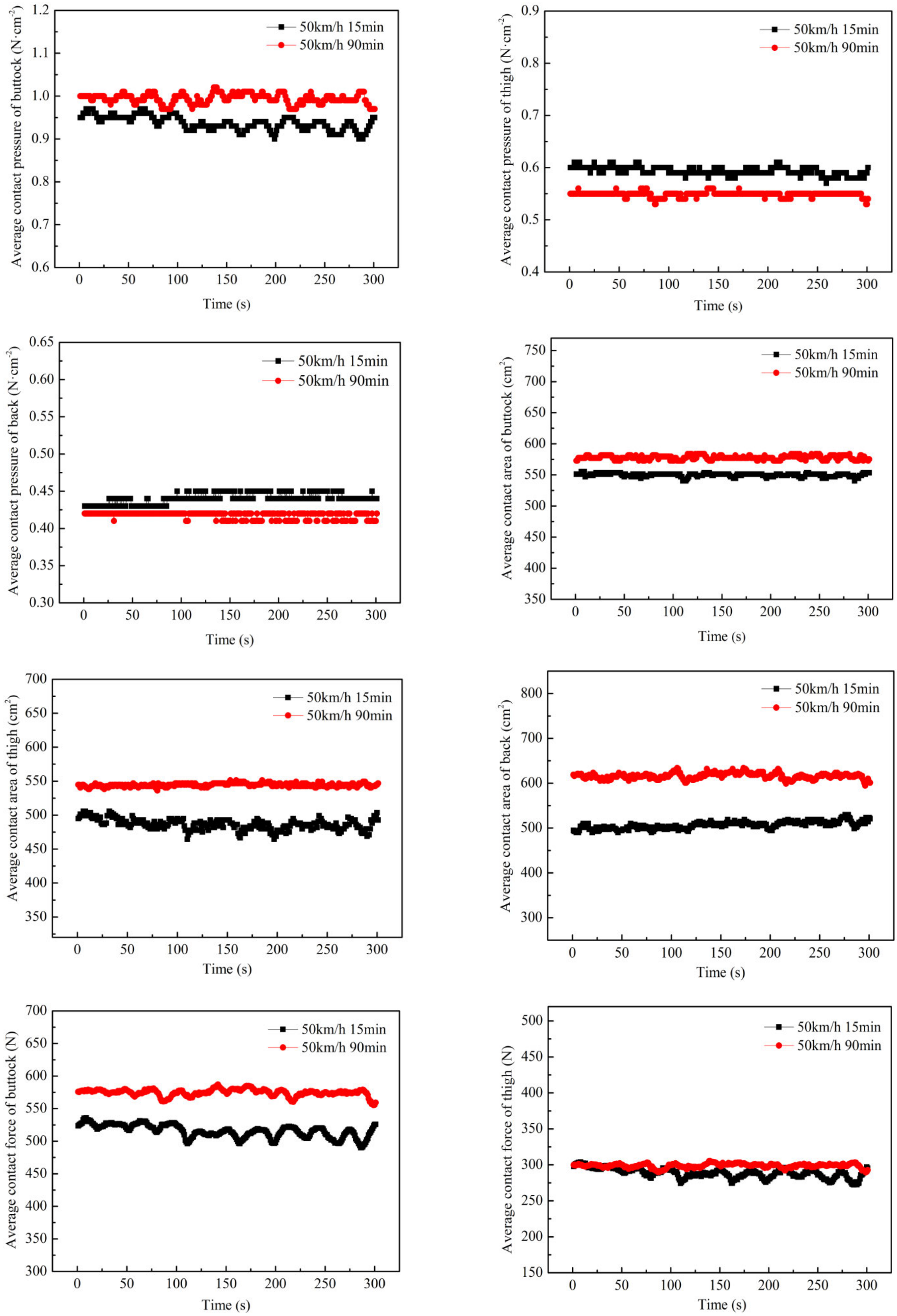

FIGURE 5. The pressure indicators during short-term and long-term driving.

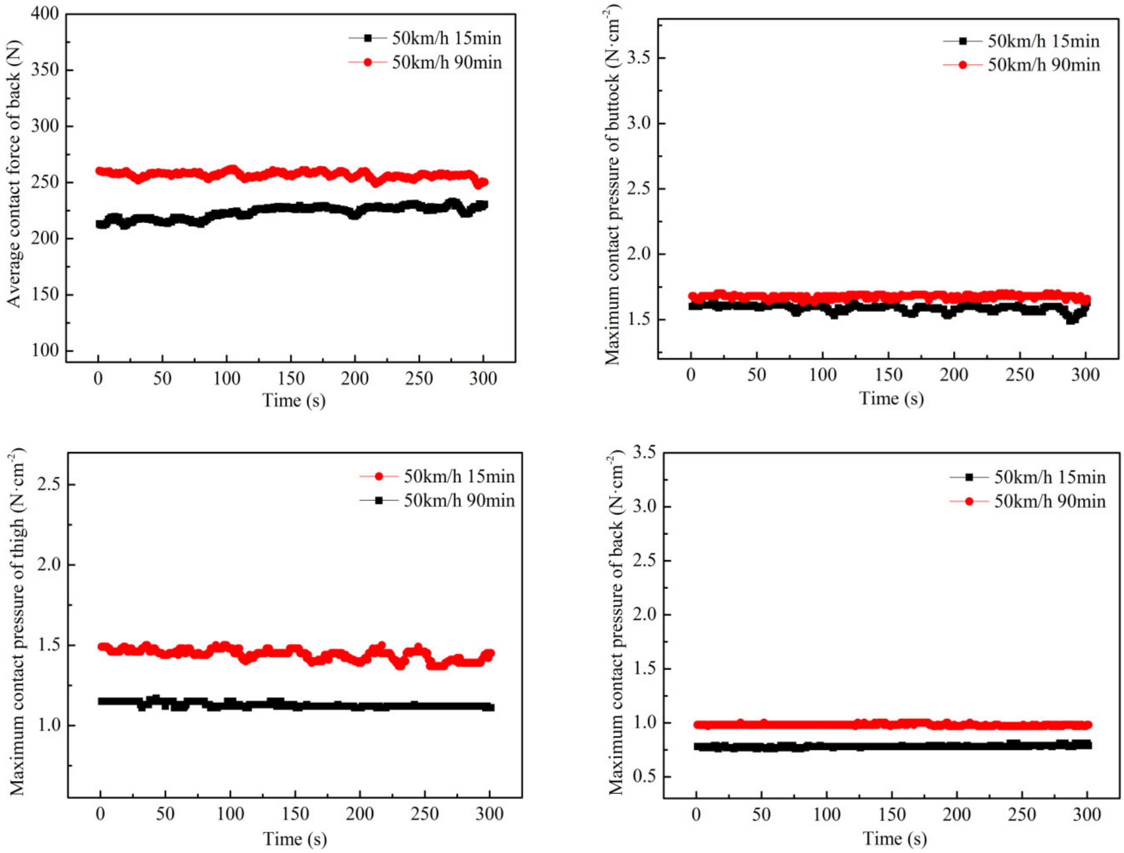

FIGURE 5. ***(Continued.)*** **The pressure indicators during short-term and long-term driving.**

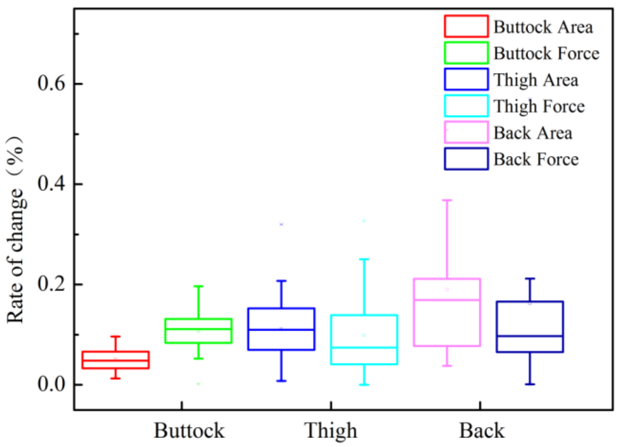

FIGURE 6. **The pressure indicators' rate of change.**

tested during 15min driving on comfort in the decreasing order as follows: the muscle activity of gastrocnemius muscle A_9, the muscle activity of rectus femoris A_7, the muscle activity of musculus triceps brachii A_8, the contact force of thigh A_4, the contact force of buttock A_2, the average contact pressure of thigh A_3, the average contact pressure of back A_5, the average contact force of back A_6 and the average contact pressure of buttock A_1. The results after 90min driving is that, the muscle activity of gastrocnemius muscle A_9, musculus triceps brachii A_8 and rectus femoris A_7 are relatively higher than others, followed by the average contact force of back A_6, and the average contact force of buttock A_2 is the smallest.

In conclusion, the paper is established on the deficiencies and limitations of the subjective and objective weighting method, and changed the way of combination weighting method's simple summation and averaging, analyzed the results from both physiology and psychology aspects according with the true condition. Applying AHP to limit entropy method to set up the comfort quantitative evaluation method, obtained the evaluation relation that combined pressure distribution, physiological information and subjective evaluation. Y_1 and Y_2 represent the driving comfort during 15min and 90min driving, repectively: $Y_1 = 0.038A_1 + 0.074A_2 + 0.071A_3 + 0.082A_4 + 0.056A_5 + 0.053A_6 + 0.175A_7 + 0.154A_8 + 0.297A_9, Y_2 = 0.052A_1 + 0.032A_2 + 0.088A_3 + 0.059A_4 + 0.076A_5 + 0.090A_6 + 0.163A_7 + 0.169A_8 + 0.271A_9$.

IV. DISCUSSION

A. THE COMFORT OF VEHICLE SEAT BASED ON PRESSURE DISTRIBUTION

The pressure and load between driver-seat interface act directly on the skin and soft tissue, they can give a perception of comfort derived from physiological sensations,

TABLE 6. Coefficients of correlation between subjective ratings and pressure variables.

Local body part	Pressure variables	Subjective rating (15min)	Subjective rating (90min)
Buttock	Average contact pressure	ρ=0.746** *p=0.001*	ρ=0.692** *p=0.003*
	Average contact area	*ρ=0.217* *p=0.420*	*ρ=0.157* *p=0.562*
	Average contact force	ρ=0.612* *p=0.012*	ρ=0.643** *p=0.007*
	Maximum contact pressure	*ρ=0.428* *p=0.098*	*ρ=0.381* *p=0.145*
Thigh	Average contact pressure	ρ=0.648** *p=0.007*	ρ=0.579* *p=0.019*
	Average contact area	*ρ=0.265* *p=0.321*	*ρ=0.362* *p=0.168*
	Average contact force	ρ=0.593* *p=0.015*	ρ=0.596* *p=0.015*
	Maximum contact pressure	*ρ=0.487* *p=0.056*	*ρ=0.388* *p=0.137*
Back	Average contact pressure	ρ=0.565* *p=0.022*	ρ=0.569* *p=0.022*
	Average contact area	*ρ=0.416* *p=0.109*	*ρ=0.487* *p=0.056*
	Average contact force	ρ=0.603* *p=0.013*	ρ=0.658** *p=0.006*
	Maximum contact pressure	*ρ=0.024* *p=0.929*	*ρ=0.457* *p=0.075*

and revealed the sustainability and pressure distribution of the seat to the human body. Compared the pressure distribution tested during 90min driving with the results of 15min, though the contact area of buttock increased, the rate change of average contact force increased higher than average contact area, the interface pressure is not well dispersed, resulting in the increase of average contact pressure of buttock. The rate change of average contact area of thigh and back is higher than average contact force, increased spine support, the interface pressure is well dispersed, resulting in the decrease of average contact pressure of thigh and back, demonstrated that the pressure distribution between different body parts-seat varied over time. The study by Park *et al.* [44], Na *et al.* [7] and Zhifei *et al.* [45] also showed that pressure distributions were affected by driving period. The correlation analysis results showed that the impact of pressure distribution on driving comfort is ultimately revealed in average contact pressure of buttock A_1, average contact pressure of thigh A_3, average contact pressure of back A_5, average contact force of buttock A_2, average contact force of thigh A_4 and average contact force of back A_6, that is, the average contact pressure and average contact force between driver-seat interface, consistent with the work of Naddeo *et al.* [11].

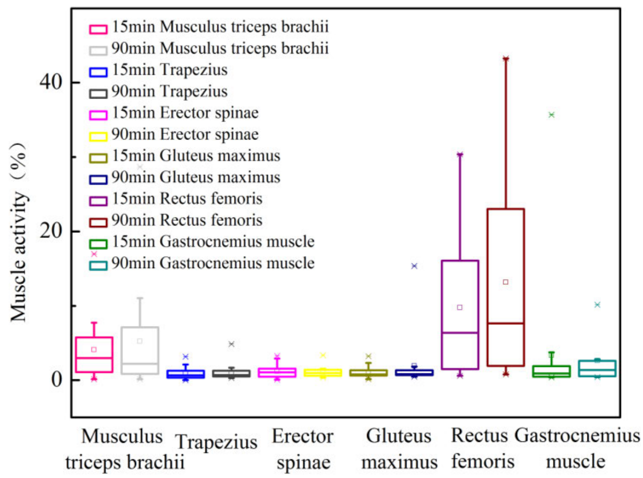

FIGURE 7. Muscle activity.

TABLE 7. The weights determined by three methods-15min.

The weighting method	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
AHP	0.138	0.109	0.072	0.110	0.164	0.087	0.089	0.100	0.132
Entropy method	0.046	0.061	0.067	0.031	0.059	0.031	0.145	0.128	0.433
AHP to limit entropy method	0.038	0.074	0.071	0.082	0.056	0.053	0.175	0.154	0.297

TABLE 8. The weights determined by three methods-90min.

The weighting method	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
AHP	0.179	0.080	0.140	0.113	0.075	0.114	0.086	0.091	0.121
Entropy method	0.044	0.089	0.077	0.029	0.060	0.092	0.165	0.202	0.242
AHP to limit entropy method	0.052	0.032	0.088	0.059	0.076	0.090	0.163	0.169	0.271

As a comprehensive perception, the impact of different body parts on comfort varies with driving duration (Zejda *et al.* [46] and Liu [47]). Combined with the weights difference of pressure indicators on comfort under short-term and long-term driving conditions, it can be seen that compared the weights of indicators on comfort measured at 15min, the impact of back and thigh local load on comfort is higher than the results of buttock when driving 90min in a comfortable posture. In driving condition, analyzed from physiological anatomy and human biomechanics that the vehicle seat while providing support for human, the load of head and torso transmitted downward to pelvis through

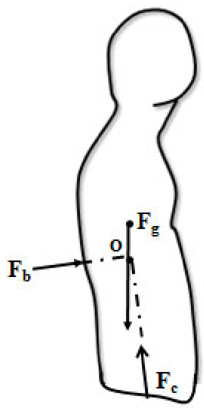

FIGURE 8. The diagram of driver's torso force.

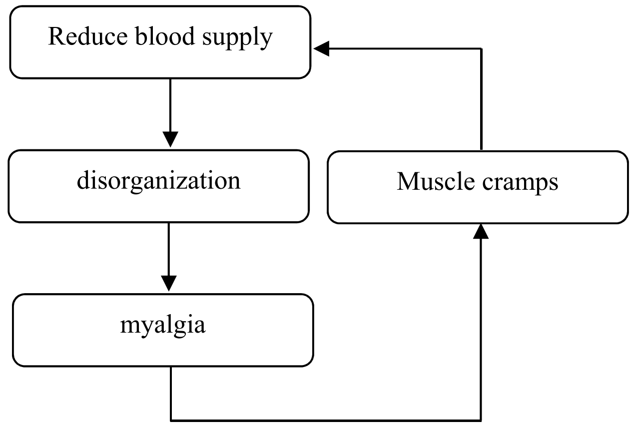

FIGURE 9. Vicious circle of discomfort.

sacroiliac joins. As show in Fig. 8, the backrest force F_b increased the horizontal force that applied to the ischial tuberosity, causing the friction on the skin and subcutaneous tissue increased, affecting the driving comfort. The thigh contains the aorta and nervous system [26], so if the pressure applied for a longer period of time, the muscles are prone to have pain and may be paralyzed, which affects the nerve conduction in lower limbs. In driving condition, the back muscles are squeezed and the abdomen muscles are tightened, so if sitting in a driving posture for a long time, resulting in the increase of muscle activity of waist, and ultimately led the muscles of waist to have pain. Therefore, the thigh and back are easily to cause discomfort than buttock with less nerve branches, then reduced the driving comfort. According to the above studies, the effects of thigh and back have more influence on driving comfort than buttock when driving in long-term period.

B. THE COMFORT OF VEHICLE SEAT BASED ON ELECTROMYOGRAPHY

Due to the differences in physiological characteristics of human body, there are also some differences in the comfort of different body part, that appears as partial discomfort in field driving. During long-term driving, if more pressure is focused on a certain body part, or the forces applied to the body part for a long term state, will enhance the permeability of blood vessels, and damage the blood flow of capillaries in nerves, affecting the nutrition of nerve roots, and that will cause numbness, pain, myasthenia and so on in human body [26], as shown in Fig. 9.

Human body is prone to fatigue during the long-term driving (Helander *et al.* [18]; Uenishi *et al.* [20]; Kim [24]). According to the studies of muscle activity and muscle mechanical characteristics during short-term and long-term driving duration, the muscle utilization rate of thigh, upper limb and calf is higher than the results of shoulder, back and buttock. When field drive, drivers handle the steering wheel and pedals with thigh, calf and upper limb, respectively, then the corresponding muscles in a continuous powering condition. As time goes on, ischemia occurs and produced the metabolite stimulates nerve endings, blocked the loosening of muscle tissues, caused fatigue, reduced the driving comfort. Therefore, in the future seat design, we should enhance the comfort of the above body parts, to minimize the impact of partial discomfort on overall comfort.

C. QUANTITATIVE EVALUATION FOR COMFORT OF VEHICLE SEAT BASED ON PRESSURE DISTRIBUTION AND PHYSIOLOGICAL INFORMATION

Using AHP to limit entropy method established the quantitative mapping relations between pressure distribution, physiological information and subjective comfort, evaluated driving comfort according with the true condition. In order to enhance the scientificity and rationality of comfort indicators' weights, applying standard deviation to analyze the similarity of weights determined by three methods, as shown in Tables 9 and 10. Study the test results present in Tables 9 and 10 show that the similarity between AHP to limit entropy method and AHP, entropy method is 0.913, 0.948 (15min) and 0.912, 0.984 (90min), respectively, are higher than the similarity between the AHP and the entropy method 0.874 (15min) and 0.911 (90min). Therefore, applying AHP to modify the weights of comfort indicators one by one, avoided the deficiency that AHP did not take the objective data into account, as well as the entropy method did not reflect the drivers' feelings, and also realized the correction among subjective evaluation and objective data, enhanced the scientificity and rationality of the indicators' weights.

TABLE 9. The similarity of the weights determined by three methods-15min.

The weighting method	AHP	Entropy method	AHP to limit entropy method
AHP	1	0.874	0.913
Entropy method	0.874	1	0.948
AHP to limit entropy method	0.913	0.948	1

By comparing the effects of indicators on driving comfort during different driving duration, we can know that:

TABLE 10. The similarity of the weights determined by three methods-90min.

The weighting method	AHP	Entropy method	AHP to limit entropy method
AHP	1	0.911	0.912
Entropy method	0.911	1	0.984
AHP to limit entropy method	0.912	0.984	1

1) The weights of the muscle activity of gastrocnemius muscle, rectus femoris and musculus triceps brachii on comfort are relatively higher than other indicators; 2) With the increase of driving duration, the weights of the average contact pressure of buttock, the average contact pressure of thigh and the average contact pressure of back impact on driving comfort is relatively higher than the results of 15min; 3) During long-term driving, the weights of the average contact pressure and average contact force on comfort is relatively lager than the results of buttock. Therefore, when handling the steering wheel and pedals, the weights of upper limb, thigh and calf impact on comfort is relatively higher. When driving in long-term period, the average contact pressure of buttock, the average contact pressure of thigh and the average contact pressure of back play a greater role in the comprehensive evaluation of comfort, the impact of the average contact pressure and average contact force of thigh and back between driver-seat on comfort is higher than impact of the average contact pressure and average contact force of buttock on it.

There are several potential limitations in this research that should be addressed. This article is about the driving comfort and quantitative evaluation method for comfort of vehicle seat in 15min and 90min driving duration, however, it is unknown if the results are appropriate for more extended driving. Meanwhile, it is difficult to conclude that the results (for 50th and 95th percentile man) are representative for all the human, whereas this study can provide an effective approach for quantitative evaluation of driving comfort.

V. CONCLUSIONS

By analyzing the difference between pressure distribution and physiological information during short-term and long-term driving duration, the correlation between pressure indicators and driving comfort, as well as the quantitative evaluation method for comfort of vehicle seat based on pressure distribution, physiological information, and subjective evaluation, the paper found that, the rate change of the average contact area between buttock-seat during long-term driving is relatively higher than the results of short-term driving duration, then the average contact pressure of buttock increased, while the results of thigh and back are reversed, the impact of thigh and back on comfort is more larger than buttock. The impact of pressure distributions on driving comfort is ultimately reflected in average contact pressure and average contact force between driver-seat interface. With the increase of driving duration, thigh, upper limbs and calf tend to fatigue or feel weary since they are in a continuous powering condition. Using the average contact pressure and average contact force between driver-seat interface during short and long-term driving, combined with physiological information, and the corresponding subjective evaluation, applying AHP to limit entropy method established the quantitative evaluation method that combined pressure distribution, physiological information and subjective evaluation, realizing the quantitative evaluation of the driving comfort, providing a theoretical basis and an effective approach for the quantitative evaluation of vehicle driving comfort.

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