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Objective Evaluation Method of Steering Comfort Based on Movement Quality Evaluation of Driver Steering Maneuver

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Abstract: The existing research of steering comfort mainly focuses on the subjective evaluation, aiming at designing and optimizing the steering system. In the development of steering system, especially the evaluation of steering comfort, the objective evaluation methods considered the kinematic characteristics of driver steering maneuver are not proposed, which means that the objective evaluation of steering cannot be conducted with the evaluation of kinematic characteristics of driver in steering maneuver. In order to propose the objective evaluation methods of steering comfort, the evaluation of steering movement quality of driver is developed on the basis of the study of the kinematic characteristics of steering maneuver. First, the steering motion trajectories of the driver in both comfortable and certain extreme uncomfortable operation conditions are detected using the Vicon motion capture system. The operation conditions are under the restrictions of the vertical height and horizontal distance between steering wheel center and the H-point of driver, and the steering resisting torque else. Next, the movement quality evaluation of driver steering maneuver is assessed using twelve kinds of evaluation indices based on the kinematic analyses of the steering motion trajectories to propose an objective evaluation method. Finally, an integrated discomfort index of steering maneuver is proposed on the basis of the regression analysis of subjective evaluation rating and the movement quality evaluation indices, including the Jerk, Discomfort and Joint Torque indices. The test results show that the proposed integrated discomfort index gives a good fitting with the subjective evaluation of discomfort, which means it can be used to evaluate or predict the discomfort level of steering maneuver. This paper proposes an objective evaluation method of steering comfort based on the movement quality evaluation of driver steering maneuver.

Keywords: steering maneuver, movement quality evaluation, driver, discomfort

1 Introduction

The dynamic control system of vehicle has been succeeded in assisting drivers, including longitudinal and lateral dynamics. Researchers have studied this control system with traction and brake control considering road friction and others[1–4]. The evaluation of this control system becomes very important, especially for the comfort evaluation. Driving comfort is an important consideration in vehicle design[5]. Taking account of the whole system of vehicle and driver, steering is very important because driver uses steering maneuver to control the vehicle direction, therefore the evaluation of steering comfort is a key portion of driving comfort. Although the evaluation of steering comfort is the important part of driving comfort, our knowledge so far is mostly the subjective feeling of driver, which shows great individual differences among different drivers. Steering comfort includes posture comfort and operation comfort. The posture comfort of driver is determined by vehicle interior layout, while the operation comfort is related to the driver's posture and the design of steering device[6]. The posture comfort is focus on the study of postural angles of segments for comfortable driving postures of drivers. Theoretical analysis and experimental study on comfortable angles was conducted from 1969 to 2010. REBIFFE[7] analyzed the driver's task and used a biomechanical model of the body to theoretically compute its comfortable posture and position based on driving tasks and visual demands. Further effort on this topic was made by GRANDJEAN[8]. PORTER, et al[9], said that published comfortable angles for driving comfort were obtained by theoretical calculations and not from observed driving postures. They conducted an experiment to investigate observed optimum driving postures and positions of the main driving controls and compared them with available data. PARK, et al[10], investigated the relationships between anthropometric characteristics(body segment lengths), preferred postural angles and seat adjustment level. ANDREONI, et al[11], presented a multi-factor method for

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the analysis of comfortable sitting posture and the resulting interactions of the car driver body with the cushion and the backrest. MOHAMAD, et al[12], recommend a range of angles for driving posture comfort from measurement of participants and found that the ranges of comfortable angles for Malaysian citizen proposed shows significant different between Caucasian and Korean populations. Though the above study on comfortable angles improved the optimal layout of car driver cabin, very little knowledge was available about how the comfort deteriorated if driving positions deviated from these postures.

The comfort evaluation in automotive ergonomics was based on the comfortable angles, which used the deviation of driver joint angles from optimal angles to estimate the discomfort feeling of driver[13]. PIAO[14] introduced the concept of loss function and developed a posture function. The loss in posture function was defined as the discomfort perception in each position. On the basis of PIAO's study, the comfort level would deteriorate if driving positions deviate from the optimal postures. ALESSANDRO, et al[15], developed a discomfort evaluating model that could provide a numerical discomfort evaluation using Matlab. The model was based on a manikin that simplified the human geometry and discomfort functions based on Luba and geometric-spatial evaluations. However posture comfort was obtained in static situations without considering the dynamic effect of operating.

BUBB, et al[13], studied the operation comfort on the basis of biomechanics and gave the conclusion that the joint angles of the human body had an important influence on the comfort feeling, while the forces to maintain the body posture had only slight effects on the comfort. DUFOUR, et al[16], put forward two hypotheses for discomfort evaluation at a joint level, including that the discomfort feeling would be increasing if the joint angle neared to its maximum value and if the joint force increased. As a consequence, they proposed the discomfort model for each degree of freedom(DOF) of each joint on the basis of the assumption that discomfort mainly depends on its joint angle and its actual joint torque. Discomfort model based on joint torque was applied to drivers' ergonomic assessment and optimization of vehicle interior design by WANG, et al[17–18]. LIU, et al[19–21], also studied the steering characteristic of driver muscles and the estimating method of driver steering efficiency to investigate the evaluation of steering comfort.

The current study of objective evaluation of steering comfort is mostly limited to joint angle and torque, which aren't considering other biomechanical characteristics of human movement. In this article, the movement quality evaluation is studied on the basis of kinematic characteristics analysis of driver steering maneuver. First, the evaluation of steering movement quality is conducted using twelve evaluation indices based on kinematics and dynamics analysis. Next, an integrated evaluation index is obtained by means of regression analysis of nine evaluation indices using stepwise method. In section 2, the experimental design and movement quality evaluation indices are presented. The evaluation results on the basis of twelve indices are presented in section 3. The discussion of evaluation of steering comfort including the integrated evaluation index is given in section 4. The concluding remarks are presented in section 5.

2 Experiment Design and Movement Quality Evaluation Indices

2.1 Experiment condition

The experiment scene is shown in Fig. 1. The experiment equipment is composed of a multi-adjustable steering mock-up, a Vicon motion capture system, a steering resisting torque simulation system and a steering wheel angle and torque transducer.

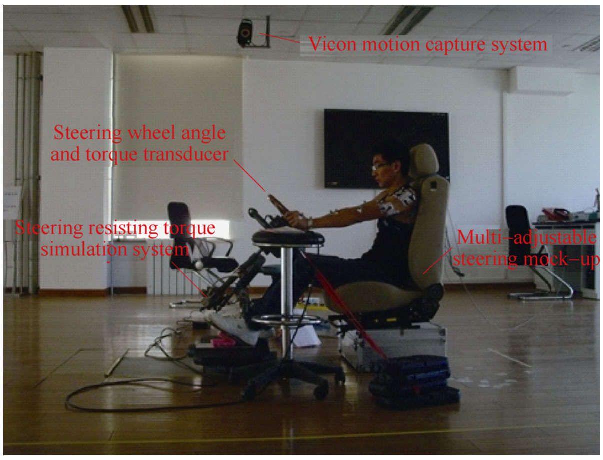

Fig. 1. Experiment scene

The multi-adjustable steering mock-up is shown in Fig. 2. The seat, a steering wheel, an accelerator pedal and a clutch pedal were used to define different driving positions. The vertical height H and horizontal distance L between steering wheel center and H-point of driver were defined as driving position variables, and the angle of the steering wheel with respect to the horizontal α could be adjusted in a wide range. All above parameters were adjusted by test subjects.

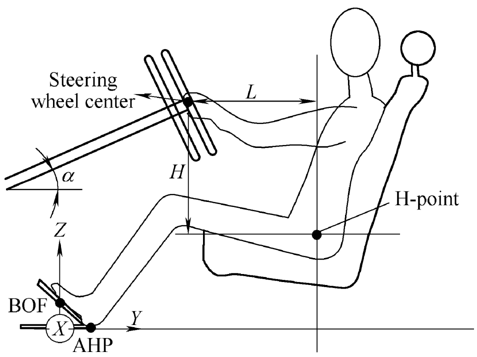

Fig. 2. Multi-adjustable steering mock-up

The Vicon motion capture system was an optoelectronic system which including six infrared cameras and was used to capture the steering movement with a frequency of 100 Hz. The steering resisting torque simulation system was used to generate different steering resisting torques to provide the steering feeling for driver.

2.2 Experiment design

Subjects were asked to perform a steering task with their left hand under three different operation conditions, which defined by three independent variables including the vertical height H, horizontal distance L and steering resisting torque T. The angle of the steering wheel with respect to the horizontal α was adjusted as 45° in the experiment, and the pedal position of the experiment mock-up could be freely adjusted by subject.

The operation conditions are presented in Table 1. These conditions include the comfortable operation condition (COC) adjusted by subject in which the subject feels the most subjective comfortable, the minimum operation condition(MIC) determined by the minimum H and L that the subject could tolerate, and the maximum operation condition(MAC) determined by the maximum H and L that the subject could tolerate. The steering resisting torque in COC is adjusted to 3 N • m in COC based on test investigation of test subjects, while it is set to be 6 N • m as the extreme value of torque in a common vehicle steering condition with a conventional power-assisted steering system.

Table 1. Steering maneuver conditions

Condition	Vertical height H	Horizontal distance L	Steering resisting torque T/(N • m)
COC	Hmid	Lmid	3
MIC	Hmin	Lmin	6
MAC	Hmax	Lmax	6

In the experiment, the participant was asked to conduct a complete steering operation with their left hand only, and to keep their torsos motionless as possible. The steering operation was a "similarly sinusoidal steering with a constant steering amplitude" that the subject firstly held at 9 o'clock position of steering wheel and then steered in clockwise direction to 11 o'clock position and next backed to 7 o'clock position and finally steered in clockwise direction to back to 9 o'clock position. The position of steering is shown in Fig. 3. The participant was required to repeat three times of above steering operation, and no other explicit control task was imposed in the test.

The markers used to present the steering maneuver trajectories of driver limb in the Vicon system were attached to the anatomical districts such as scapula, acromion, the middle of upper arm, lateral epicondyle, the middle of lower arm, ulnar styloid, radius styloid and metacarpophalangeal joint of the index finger of the left limb(Fig. 4).

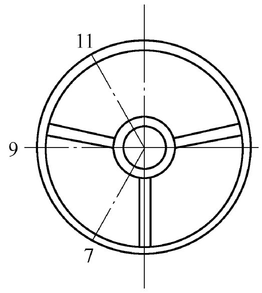

Fig. 3. Positions of the steering wheel

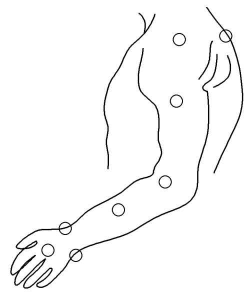

Fig. 4. Positions of the markers

At the end of a test, participant was asked to give a global discomfort rating score for the steering operation. The discomfort was evaluated using a slightly modified category partition scale CP-50[22](Fig. 5). The perceived discomfort ratings would be translated into the original CP-50 scale ranging from 0 to 50 or more.

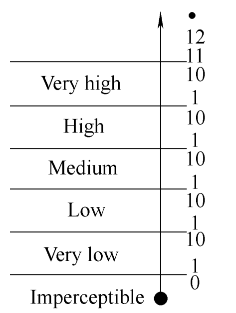

Fig. 5. Slightly modified category partition CP-50 scale

Four male drivers participated in the experiment and gave their informed consent to the procedure, which was approved by the local ethical committee. The main characteristics of these subjects are shown in Table 2. All subjects did not have any joint diseases or musculo-skeletal abnormalities. They were instructed to wear clothing and footwear comfortable for driving. The purposes and procedures of the experiment were explained in detail before participating in the experiment.

Table 2. Main characteristics of the subjects

Subject	Age	Stature Hs/mm	Weight Ms/kg	Driving years
No. 1	24	1650	58	1
No. 2	25	1800	63	6
No. 3	26	1760	65	5
No. 4	22	1680	62	2

2.3 Movement quality evaluation indices

2.3.1 Movement time

Movement time(MT) is defined as the time that the subject spends in performing the movement task[23].

2.3.2 Total distance

The total distance(TD) travelled by the subject during the movement is defined as[23]

$$TD = \sum_{k=1}^{N} \left\{ \left[x(k+1) - x(k)\right]^2 + \left[y(k+1) - y(k)\right]^2 + \left[z(k+1) - z(k)\right]^2 \right\}^{\frac{1}{2}}, \tag{1}$$

where $x(k)$, $y(k)$, $z(k)$ are the X, Y, and Z coordinates of the marker at the sampled time k. N represents the sample length.

2.3.3 Velocity

Velocity is one of the most widely used indices in movement quality evaluation[24]. The instantaneous velocity is calculated from two adjacent positions as[25]

$$v(k) = \frac{1}{\Delta t} \left\{ \left[x(k+1) - x(k)\right]^2 + \left[y(k+1) - y(k)\right]^2 + \left[z(k+1) - z(k)\right]^2 \right\}^{\frac{1}{2}}, \tag{2}$$

where Δt is the sampling interval.

The velocity index $\overline{v}$ is the average instantaneous velocity throughout a task, which can be defined as

$$\overline{v} = \frac{1}{N} \sum_{k=1}^{N} v(k). \tag{3}$$

2.3.4 Angular velocity

The instantaneous angular velocity is defined as

$$\omega(k) = \frac{q(k+1) - q(k)}{\Delta t}, \tag{4}$$

where $q(k)$ is the joint angle at the sampled time k.

The angular velocity index $\overline{\omega}$ is the average absolute value of the instantaneous angular velocity throughout a task, which can be defined as:

$$\overline{\omega} = \frac{1}{N} \sum_{k=1}^{N} \left|\omega(k)\right|. \tag{5}$$

2.3.5 Energy

Energy index represents the energy consumption in the whole movement, including the total kinetic energy index and total energy consumption index.

(1) Total Kinetic Energy

The kinetic energy at the sampled time k is computed as follows [26]:

$$E(k) = \frac{m}{2} v(k)^2, \tag{6}$$

where m is the mass of the human body, $v(k)$ is the instantaneous velocity at the sampled time k.

The total kinetic energy is defined as[22]

$$E_{\mathrm{T}} = \sum_{k=1}^{N} E(k). \tag{7}$$

(2) Total Energy Consumption

The instantaneous power is the time rate of change of the kinetic energy E[26]:

$$\Delta E(k) = \frac{E(k+1) - E(k)}{\Delta t}. \tag{8}$$

The total energy consumed in the whole movement is calculated as follows[26]:

$$TE = \sum_{k=1}^{N} \Delta E(k) \bullet \Delta t. \tag{9}$$

2.3.6 Smoothness

It is believed that natural movements are characteristically as smooth as possible if there is not any other overriding concern such as the movement speed or accuracy[27]. Smoothness index reflects the smoothness of movement and the human controlling ability of motion stability. The smaller the smoothness index value is, the smoother the motion is[28]. There are 3 indices of smoothness that will be introduced below.

(1) Average instantaneous smoothness $\overline{S}$

The instantaneous smoothness is defined as[25]

$$S(k) = \left|j_x(k)\right| \bullet \left|j_y(k)\right| \bullet \left|j_z(k)\right|, \tag{10}$$

where $j_x(k)$, $j_y(k)$, $j_z(k)$ are the differential of acceleration in X, Y, and Z axis directions respectively.

The $\overline{S}$ index is the average instantaneous smoothness S throughout a task, and is defined as:

$$\overline{S} = \frac{1}{N} \sum_{k=1}^{N} S(k). \tag{11}$$

(2) Smoothness J[27] can be expressed as

$$J = \frac{1}{N} \sum_{k=1}^{N} \sqrt{j_x(k)^2 + j_y(k)^2 + j_z(k)^2}. \tag{12}$$

(3) Smoothness C[29–30] can be expressed as

$$C = \frac{1}{2}\sum_{k=1}^{N}\left(j_x(k)^2 + j_y(k)^2 + j_z(k)^2\right). \qquad (13)$$

2.3.7 Jerk

Jerk is an index derived from the acceleration, and reflects the movement smoothness of the moving limb segment.

(1) Average translation jerk $\overline{j_a}$

The instantaneous translation jerk is obtained from the acceleration:

$$j_a(k) = \frac{a(k+1) - a(k)}{\Delta t}, \qquad (14)$$

where $a(k)$ is the instantaneous acceleration of mass center of the body at the sampled time k.

The $\overline{j_a}$ index is the average instantaneous translation jerk throughout a task, and is defined as

$$\overline{j_a} = \frac{1}{N}\sum_{k=1}^{N}\left|j_a(k)\right|. \qquad (15)$$

(2) Average rotation jerk $\overline{j_\alpha}$

The instantaneous rotation jerk is obtained from the angular acceleration:

$$j_\alpha(k) = \frac{\alpha(k+1) - \alpha(k)}{\Delta t}, \qquad (16)$$

where $\alpha(k)$ is the instantaneous angular acceleration of the joint at the sampled time k.

The $\overline{j_\alpha}$ index is the average instantaneous rotation jerk throughout a task, and is defined as[27]:

$$\overline{j_\alpha} = \frac{1}{N}\sum_{k=1}^{N}\left|j_\alpha(k)\right|. \qquad (17)$$

2.3.8 Joint displacement

Assuming that neutral position q^N represents a relatively comfortable position, joint displacement is the angular offset from neutral position. The total joint displacement of all joints can be represented as follows[30–31]:

$$f_{\text{Displ}} = \sum_{i=1}^{n}\sum_{k=1}^{N} DOF\omega_i (q_i(k) - q_i^N)^2, \qquad (18)$$

where n is the total number of degree of freedom(DOF), N is the sample length, $q_i(k)$ is the angular displacement of the ith DOF at the sampled time k, q_i^N is the neutral position of the ith DOF, $DOF\omega_i$ is a weight function assigned to each DOF which is used to stress the importance of particular DOF.

2.3.9 Discomfort

The discomfort index is defined as another parameter of joint displacement. The discomfort function is given as follows[30, 32]:

$$f_{\text{Discomf}} = \sum_{i=1}^{n}\sum_{k=1}^{N} DOF\omega_i \left(\frac{q_i(k) - q_i^N}{q_i^{\text{U}} - q_i^{\text{L}}}\right)^2, \qquad (19)$$

where q_i^{U} and q_i^{L} are the upper limit and lower limit of q_i.

2.3.10 Potential energy

Potential energy index represents the change in potential energy. It can be written in the form of a weighted sum as[31]

$$f_{\text{Potential}} = \sum_{i=1}^{n}\sum_{k=1}^{N} (m_i g)^2 (h_i(k) - h_i^N)^2, \qquad (20)$$

where h_i^N is the vertical height of the center of mass for the ith body lumped mass with the arms put down naturally and parallel to the torso. $h_i(k)$ is the vertical height of the center of mass for the ith body lumped mass at the sampled time k. m_i is the mass of each body lumped mass, g is the gravity constant, $(m_i g)^2$ represents the weight of the ith body part, n is the number of the body lumped masses involving in the motion, N represents the sample length.

2.3.11 Joint torque

DUFOUR, et al[16], used the relative torque(the actual joint torque relative to its individual maximum torque) to measure discomfort. Here we use the actual joint torque as the evaluation index in this paper which is defined as

$$f_{\text{Torque}} = \sum_{i=1}^{n}\sum_{k=1}^{N} DOF\omega_i \left|\tau_i(k)\right|, \qquad (21)$$

where $\tau_i(k)$ is the joint torque of the ith DOF at the sampled time k, $DOF\omega_i$ is a weight function used to distribute the importance of the index among all DOFs.

2.3.12 Joint work

Joint work represents the energy consumed by the joint in any given motion and is calculated as follows[33]:

$$f_{\text{Work}} = \sum_{i=1}^{n}\sum_{k=1}^{N} \left|\tau_i(k)\dot{q}_i(k)\right| \cdot \Delta t, \qquad (22)$$

where $\tau_i(k)$ is the joint torque of the ith DOF at the sampled time k, $\dot{q}_i(k)$ is joint velocity of the ith DOF, Δt represents the sampling interval.

3 Experiment Results of Movement Quality Evaluation

Fig. 6 and Fig. 7 illustrate the spatial trajectories of wrist and elbow in three conditions of subject No. 4. The displacement of scapula and acromion were very little because subject was asked to keep him torsos motionless, the trajectory of shoulder therefore was not investigated in this paper. The wrist trajectories in three operation conditions were less different compared with the elbow trajectories, because the wrist was near to steering wheel that approximately moved with the wheel together in any operation condition. The elbow joint trajectories in steering were much different in different operation conditions, which means the elbow joint had more flexibility compared with the shoulder and wrist joints. The discomfort evaluation therefore was studied on the basis of the kinematic analysis of elbow joint in this study.

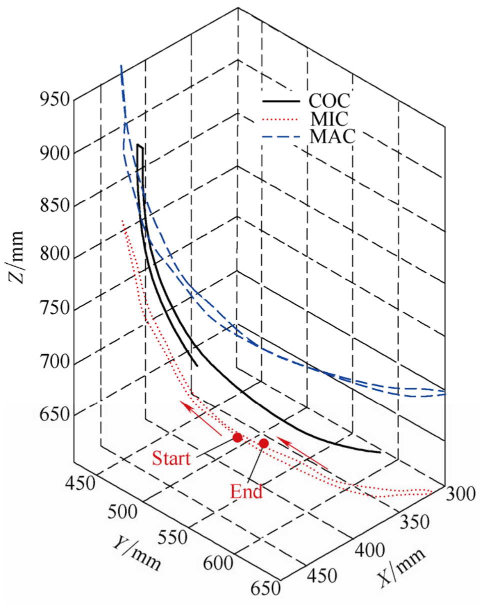

Fig. 6. Spatial trajectories of wrist of three conditions

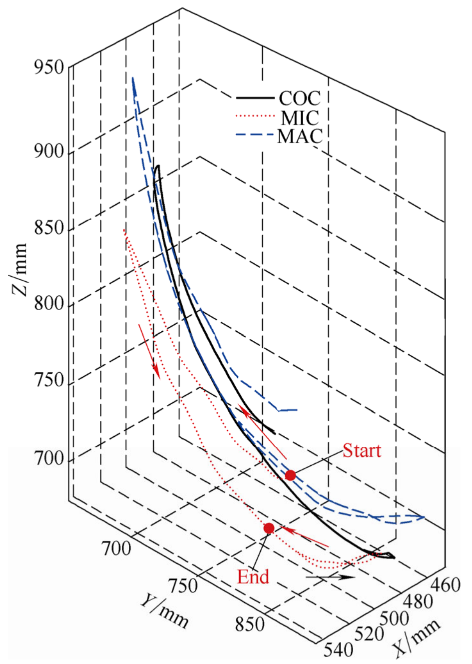

Fig. 7. Spatial trajectories of elbow of three conditions

Movement quality assessment was conducted on the basis of the average of 3 test results of each experiment by means of twelve evaluation indices. Joint displacement, discomfort, potential energy, joint torque and joint work in these evaluation indices related to the upper limb, while other indices focused on the elbow joint. And because the steering resisting torque would change to assisting torque with steering direction in the experiments, thus meaning the joint torque would be very difficult to calculate in whole test, the evaluations of joint torque and joint work therefore were only base on the upper limb motion from 9 o'clock to 11 o'clock position when steered along clockwise.

The mass of the upper limb was normalized to 1(m=1) in energy calculation. For potential energy calculation, we assumed that the primary segments of the upper limb had three lumped masses including the upper arm, the forearm and the hand.

3.1 Movement quality evaluation indices

Table 3 gives the evaluation indices of different operation conditions of subject No. 4. It can be seen that the total distance (TD), average velocity ($\overline{v}$), total kinetic energy (E_T), total energy consumption (TE), the smoothness ($\overline{S}$, J, C), average translation jerk ($\overline{j}_a$), joint displacement (f_{Displ}), discomfort ($f_{Discomf}$), joint torque (f_{Torque}) and joint work (f_{Work}) in COC have the smallest value of three conditions, while the angular velocity ($\overline{\omega}$), average rotation jerk ($\overline{j}_\alpha$) and potential energy ($f_{Potential}$) in COC have the middle value. It also can be noticed that COC has the shortest movement time (MT). Most of above evaluation indices show that the driver has the higher level of movement quality when he steers in his comfortable operation condition.

3.2 Normalized movement quality evaluation indices

Table 4 shows the example of the mean, standard deviations (SD) and discrete degree (DD) of the quality evaluation indices of subjects in COC. For the total distance (TD), there was almost no difference among the subjects with the dispersion of 6.71%. For the indices of $\overline{v}$, E_T, J, $\overline{j}_a$, and f_{Torque}, they were almost at the same level because the dispersions of subjects were less than 20%. For MT, $\overline{\omega}$, TE, C, $\overline{j}_\alpha$, f_{Displ}, $f_{Discomf}$ and f_{Work}, the dispersions were between 30% and 40%, which indicated that there were large differences between different subjects. For $\overline{S}$ and $f_{Potential}$, there were even larger differences between subjects because the dispersions were 75.8% and 46.93% respectively.

It is clear that the individual differences can be obviously found between different subjects even evaluating with the same index. The physiology state and movement habits of subjects are two factors which will affect the evaluation of movement quality. The data therefore will be normalized for each subject separately in order to reduce the subject effect.

Table 3. Movement quality evaluation indices of No. 4

Condition	Movement time MT/s	Total distance TD/mm	Velocity $\bar{v}$ /(mm • s^{-1})	Angular velocity $\bar{\varpi}$ /((°) • s^{-1})	Total kinetic energy E_T/J	Total energy consumption TE/J	Average instantaneous smoothness $\bar{S}$ /(mm^3 • s^{-9})	Smoothness J/(mm • s^{-3})
COC	4.05	534.08	131.9	12.06	4.52	0.13	6.31×10^9	2828.73
MIC	3.57	534.66	149.8	11.97	5.39	0.24	7.45×10^9	4009.87
MAC	4.1	678.09	165.43	13.45	7.69	0.32	2.23×10^{10}	4841.37

Condition	Smoothness C/(mm^2 • s^{-6})	Average translation jerk $\bar{j}_a$ /(mm • s^{-3})	Average rotation jerk $\bar{j}_\alpha$ /((°) • s^{-3})	Joint displacement f_{Displ} /((°)^2)	Discomfort $f_{Discomf}$	Potential energy $f_{Potential}$ /J^2	Joint torque f_{Torque} /(N • m)	Joint work f_{Work} /J
COC	2.3×10^7	2901.59	502.53	3.64×10^6	149.83	2937.89	2054.35	2.51
MIC	3.62×10^7	4339.47	389.13	3.92×10^6	164.46	1751.6	2713.78	5.67
MAC	6.15×10^7	4657.68	668.55	4.78×10^6	181.96	3718.75	2555.06	6.85

Table 4. Movement quality evaluation indices for COC

No.	Movement time MT/s	Total distance TD/mm	Velocity $\bar{v}$ /(mm • s^{-1})	Angular velocity $\bar{\varpi}$ /((°) • s^{-1})	Total kinetic energy E_T/J	Total energy consumption TE/J	Average instantaneous smoothness $\bar{S}$ /(mm^3 • s^{-9})	Smoothness J/(mm • s^{-3})
1	4.54	589.98	130	17.24	5.06	0.19	1.39×10^{10}	3492.25
2	7.19	622.96	93.26	9.52	4.09	0.12	2.2×10^9	2164.22
3	3.81	557.8	146.47	19.7	6.15	0.25	4.41×10^9	2843.30
4	4.05	534.08	131.9	12.06	4.52	0.13	6.31×10^9	2828.73
Mean	4.9	576.21	125.41	14.63	4.96	0.17	6.71×10^9	2832.13
SD	1.56	38.68	22.66	4.66	0.89	0.06	5.08×10^9	542.22
DD	31.82%	6.71%	18.07%	31.87%	17.96%	34.9%	75.8%	19.15%

No.	Smoothness C/(mm^2 • s^{-6})	Average translation jerk $\bar{j}_a$ /(mm • s^{-3})	Average rotation jerk $\bar{j}_\alpha$ /((°) • s^{-3})	Joint displacement f_{Displ} /((°)^2)	Discomfort $f_{Discomf}$	Potential energy $f_{Potential}$ /J^2	Joint torque f_{Torque} /(N • m)	Joint work f_{Work} /J
1	4×10^7	2790.05	537.33	7.19×10^6	302.78	3544.07	2057.69	4.97
2	2.02×10^7	2042.43	207.98	6.98×10^6	271.53	6796.02	2854.28	5.55
3	2.02×10^7	2790.62	472.07	4.04×10^6	198.62	2777.61	2215.13	6.92
4	2.3×10^7	2901.59	502.53	3.64×10^6	149.83	2937.89	2054.35	2.51
Mean	2.59×10^7	2631.17	429.98	5.46×10^6	230.69	4013.9	2295.36	4.99
SD	9.53×10^6	395.98	150.38	1.88×10^6	69.36	1883.89	380.09	1.84
DD	36.85%	15.05%	34.97%	34.46%	30.07%	46.93%	16.56%	36.95%

For each index, the minimum and maximum values of subjects in three conditions were set as 0 and 1 respectively, and the index value was normalized on the basis of the minimum and maximum values. Table 5 presents the means and standard deviations of the normalized indices of all subjects in different conditions. In order to obtain a clear illustrating of these normalized indices, we added 1 for each value in Fig. 8.

Table 5. Normalized movement quality evaluation indices

Condition	Movement time MT/s	Total distance TD/mm	Velocity $\bar{v}$ /(mm • s^{-1})	Angular velocity $\bar{\varpi}$ /((°) • s^{-1})	Total kinetic energy E_T/J	Total energy consumption TE/J	Average instantaneous smoothness $\bar{S}$ /(mm^3 • s^{-9})	Smoothness J/(mm • s^{-3})
COC	0.58±0.46	0	0.15±0.19	0.44±0.49	0.05±0.06	0	0.05±0.11	0
MIC	0.47±0.45	0.43±0.42	0.48±0.41	0.1±0.2	0.39±0.43	0.54±0.33	0.41±0.41	0.62±0.27
MAC	0.5±0.58	0.86±0.29	0.75±0.5	0.82±0.36	0.75±0.5	0.77±0.45	0.75±0.5	0.82±0.36

Condition	Smoothness C/(mm^2 • s^{-6})	Average translation jerk $\bar{j}_a$ /(mm • s^{-3})	Average rotation jerk $\bar{j}_\alpha$ /((°) • s^{-3})	Joint displacement f_{Displ} /((°)^2)	Discomfort $f_{Discomf}$	Potential energy $f_{Potential}$ /J^2	Joint torque f_{Torque} /(N • m)	Joint work f_{Work} /J
COC	0	0	0.12±0.19	0.03±0.06	0.09±0.18	0.54±0.37	0	0
MIC	0.59±0.3	0.79±0.17	0.15±0.18	0.63±0.43	0.72±0.32	0	0.87±0.16	0.86±0.16
MAC	0.84±0.33	0.78±0.44	1	0.54±0.54	0.54±0.53	0.92±0.15	0.75±0.36	0.69±0.42

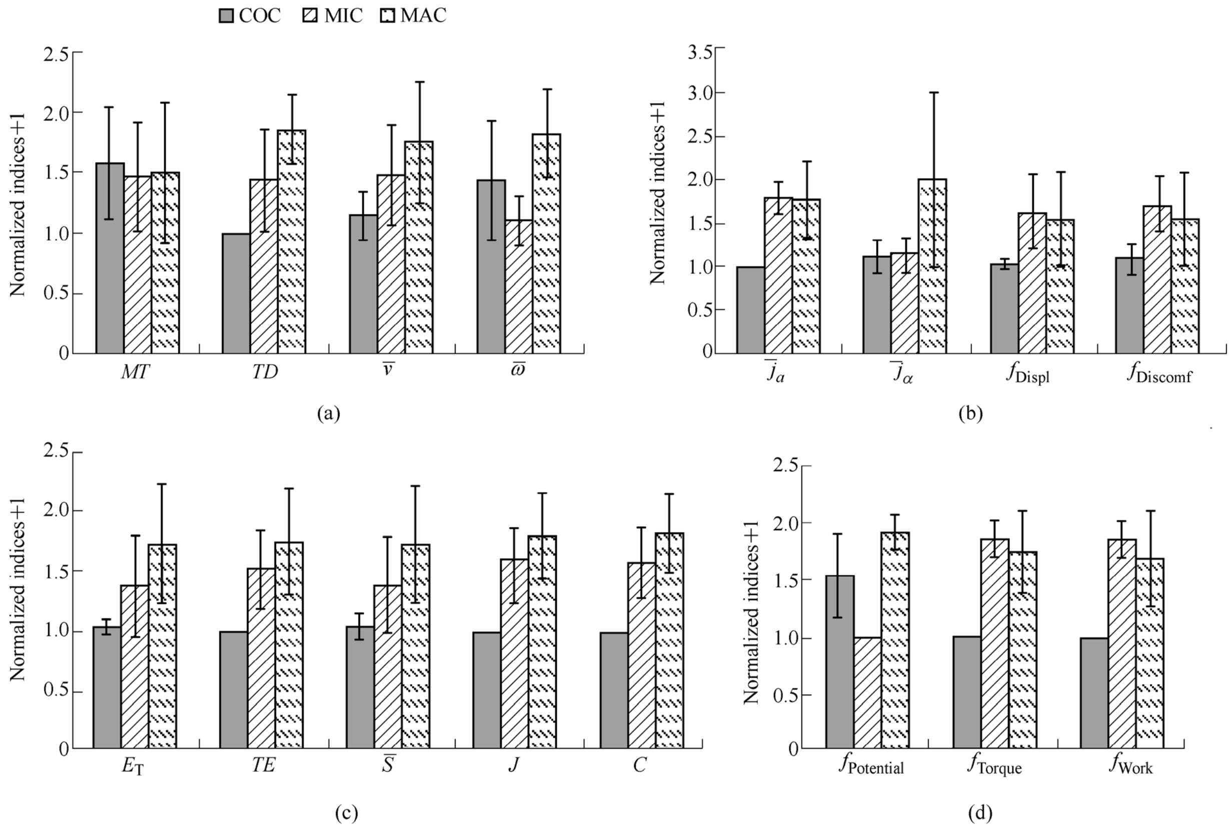

Fig. 8. Normalized movement quality evaluation indices

The normalized results showed that COC had the minimum values of indices *TD*, E_T, *TE*, $\overline{S}$, *J*, *C*, $\overline{j}_a$, $\overline{j}_\alpha$, f_{Displ}, $f_{Discomf}$, f_{Torque} and f_{Work}. The deviations of *TD*, *TE*, *J*, *C*, $\overline{j}_a$, f_{Torque} and f_{Work} were all 0. Moreover, COC also had the faster angular velocity $\overline{\omega}$, the slowest velocity $\overline{v}$ and longest movement time *MT*.

4 Evaluation of Steering Comfort

4.1 Discomfort evaluation indices

Driver will feel discomfortable if the distance between steering wheel center and H-point exceeds the 'appropriate distance' of himself/herself, such as too high or too low, too far or too near. The quality of steering performance will also become worse with the changing of above distance. Some of twelve movement evaluation indices therefore may reflect the subjective discomfort perception of driver, which means these indices can be used to evaluate the steering comfort.

In COC, subjects had the smallest *TD*, which indicated that all subjects chose the shortest route distance to complete steering maneuver to make them feel comfortable. The subjects also had the faster angular velocity $\overline{\omega}$, the slowest velocity $\overline{v}$ and longest movement time *MT* in COC, which meant that subjects might choose a more natural and comfortable speed to perform the steering but not to travel as fast as possible.

The minimum values of E_T, *TE*, f_{Work}, $\overline{S}$, *J*, *C*, $\overline{j}_a$, $\overline{j}_\alpha$, f_{Torque}, f_{Displ} and $f_{Discomf}$ in COC illustrated that subjects would have the best motion smoothness and stability, the least joint work and energy consumption when steered in their subjective comfortable conditions. The movement quality evaluation results of the present study accorded with the hypothesis that human movements should obey the principle of minimum distance, work and discomfort, the best smoothness.

In MIC, subjects had the smallest potential energy $f_{Potential}$ with the deviation of 0, showing that the change in potential energy was the least in MIC. The potential energy index was related to different steering movement amplitudes, but not reflects the steering comfort.

Comparing with COC, MIC and MAC had the higher value on distance, energy, smoothness, jerk, joint displacement, discomfort, joint torque and joint work, implying that it would consume more energy to perform steering and have worse motion smoothness and stability.

In summary, some of the movement quality evaluation indices can be used to evaluate the discomfort, including *TD*, E_T, *TE*, f_{Work}, $\overline{S}$, *J*, *C*, $\overline{j}_a$, $\overline{j}_\alpha$, f_{Torque}, f_{Displ} and $f_{Discomf}$ (seen in Table 5).

4.2 Integrated discomfort index

Table 6 displays the subjective discomfort rating scores (D_{disc}), while Table 7 presents the results of correlation using Pearson analysis between the normalized movement quality evaluation indices and normalized perceived/subjective discomfort evaluation. The perceived discomfort ratings were normalized by means of the same method as evaluation indices in section 3.2.

Table 6. Subjective discomfort rating scores(D_{disc})

Subject	COC	MIC	MAC
N0.1	0	41	38
N0.2	0	39	38
N0.3	0	35	35
N0.4	0	32	28

Table 7. Correlation analysis between movement quality evaluation indices and subjective discomfort evaluation

	Movement time MT	Total distance TD	Velocity $\overline{v}$	Angular velocity $\overline{\omega}$	Total kinetic energy E_T	Total energy consumption TE	Average instantaneous smoothness $\overline{S}$	Smoothness J
Subjective discomfort rating scores D_{disc}	–0.142	0.682*	0.518	–0.006	0.55	0.716**	0.56	0.811**
	Smoothness C	Average translation jerk $\overline{j}_a$	Average rotation jerk $\overline{j}_\alpha$	Joint displacement f_{Displ}	Discomfort $f_{Discomf}$	Potential energy $f_{Potential}$	Joint torque f_{Torque}	Joint work f_{Work}
Subjective discomfort rating scores D_{disc}	0.801**	0.845***	0.463	0.568*	0.597*	–0.129	0.878***	0.827***

Note: ***—Correlation is significant at the 0.001 level, **—Correlation is significant at the 0.01 level, *—Correlation is significant at the 0.05 level

On the basis of the Pearson analysis, it showed that there were very strong positive correlations between subjective discomfort evaluation and some movement quality evaluation indices, such as J, C, $\overline{j}_a$, f_{Torque}, and f_{Work}. And strong positive correlations were found between subjective discomfort evaluation and the evaluation indices of TD, TE, f_{Displ}, and $f_{Discomf}$. The correlation analysis was also confirmed the point that the movement quality evaluation indices of steering maneuver could be used to evaluate steering discomfort, especially the indices of TD, TE, J, C, $\overline{j}_a$, f_{Torque}, f_{Work}, f_{Displ}, and $f_{Discomf}$. Therefore, we could use these indices to obtain an integrated evaluation index to evaluate steering discomfort.

In order to propose the integrated index, a multi-linear regression using the stepwise method is conducted. The method is described as follows:

(1) Select TD, TE, J, C, $\overline{j}_a$, f_{Torque}, f_{Work}, f_{Displ}, and $f_{Discomf}$ as the independent variables. And choose the subjective discomfort(perceived discomfort ratings) as the dependent variable.

(2) Calculate the correlation coefficient between each independent variable and the dependent variable(seen in Table 7). Next order the independent variables according to the absolute values of their correlation coefficients.

(3) Establish a simple linear regression equation using the independent variable with the largest absolute value of correlation coefficient. Next verify the equation's significance. If the result was significant, proceed to step (4). Otherwise, stop the establishment of the model.

(4) Add and eliminate other independent variables, and update the regression model.

The integrated index on the basis of the above evaluation indices was established using stepwise method as follows:

$$D_{disc}^{prediction} = \left|0.063\,8 + 0.655\,6 * \overline{j}_a - 0.366\,9 * f_{Discomf} + 0.756\,1 * f_{Torque}\right|,$$
$$\text{Adj } R^2 = 0.926. \quad (23)$$

Table 8 shows the comparison results between perceived discomfort ratings from experimental data and predicted discomfort ratings by means of the integrated index. It can be seen that the maximum error of predicted value is 18.96%, but most of them are less than 14%, the integrated index therefore would be used to predict or evaluate steering comfort of driver.

Table 8. Comparison between perceived discomfort ratings and predicted discomfort ratings

Parameter	No. 1			No. 2			No. 3			No. 4		
Subjective discomfort rating scores D_{disc}	0	1	0.927	0	1	0.974	0	1	1	0	1	0.875
Predicted discomfort rating scores $D_{disc}^{prediction}$	0.064	0.896	0.833	0.064	0.863	1.109	0.069	0.931	0.906	0.064	1.190	0.927
Absolute error Δ_{AD}	0.064	0.104	0.094	0.064	0.137	0.134	0.069	0.069	0.094	0.064	0.19	0.052
Relative error Δ_{RD} /%	–	10.39	10.09	–	13.69	13.78	–	6.94	9.4	–	18.96	5.9

5 Conclusions

(1) The movement quality evaluation of driver steering was analyzed on the basis of the knowledge of biomechanical characteristics. Movement quality evaluation indices proposed in this paper included the trajectory of human motion and its pluri-derivative, the total energy consumed in the whole movement, controlling ability of motion stability and the comfort of the joint angle, reflecting the movement quality significantly.

(2) On the basis of the complexity of human limb structure and the variety of human movement, it was necessary to be normalized by individual when evaluating steering maneuver in order to minimize the influence of different individuals. Comparing the movement quality evaluation of different subjects with different operation conditions(including the comfortable operation condition (COC), the minimum operation condition(MIC) and the maximum operation condition(MAC)), it was observed that in COC the participants had the minimum values of indices of *TD*, *TE*, *J*, *C*, $\overline{j}_a$, f_{Displ}, f_{Discomf}, f_{Torque}, and f_{Work}. The results showed that the participants could chose a short travel path to accomplish the steering motion with less energy consumption and better motion control ability for COC, which was consistent with the subjective feeling.

(3) An integrated discomfort index was proposed on the basis of *TD*, *TE*, *J*, *C*, $\overline{j}_a$, f_{Displ}, f_{Discomf}, f_{Torque}, and f_{Work}. This index was defined as a weighted sum of objective discomfort evaluation indices using a linear regression on experimental data. The proposed integrated discomfort index succeeded in giving a good consistent with subjective evaluation of discomfort. The integrated discomfort index expression presented in this paper was a normalized regression function, in order to minimize the influence of the subject's specific discomfort threshold.

In summary, the objective discomfort evaluation indices based on steering movement quality evaluation were helpful for evaluating the steering comfort, and an integrated discomfort index of steering maneuver was proposed. These objective evaluation indices could be studied in future considering the steering characteristic of driver muscles and the estimating method of driver steering efficiency to propose a specific objective evaluation index, which will assist the subjective evaluation in steering comfort evaluating.

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