Estimation and compensation of angular misalignment at robot end brush roller-workpiece contact interface via elastic contact force perception

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Abstract
When the non-standard customized brush roller tool is used for robotic grinding of large-scale components, the clamping and positioning error of the brush roller at the end of the robot is extremely easy to cause misalignment at the brush roller-workpiece contact interface, which will affect the machining accuracy and surface quality. In order to ensure the parallel contact between the brush roller and the workpiece surface during the machining process, a calculation model of the angular misalignment at the brush roller-workpiece contact interface is proposed based on the elastic contact force perception, and then the accurate positioning of the robot end brush roller is realized by a fast compensation method. Firstly, according to the geometric force relationship between the brush roller and the workpiece, as well as the determined brush roller material property parameters, the estimation model of angular misalignment is established. Secondly, both the axial force and normal torque at the time of initial contact detected by the force-controlled sensor are regarded as the input parameters in the model. Furthermore, the calculated brush roller-workpiece contact offset is used as the geometric error compensation amount, and the brush roller is deflected to achieve error compensation by the robot RAPID program control command.

The finite element simulation results are compared with the theoretical calculation values, and the average relative error is 15.1%. The experiment on robotic grinding and brushing of high-speed rail body indicates that the compensated angle can be reduced to 0.024° from an average of 0.179° before compensation, coupled with uniform material removal depth. The proposed method can significantly improve the contour accuracy of large-scale components.

Keywords Robotic grinding · Brush roller tool · Force control · Angular misalignment estimation · Geometric error compensation

1 Introduction
Robotic grinding technology is an important means to improve the high-efficiency and high-quality machining in the fields of aerospace, rail transit, and automobile [1]. At present, it is generally considered that the machining geometric error is the main problem to restrict the application of robotic grinding in the machining of large and complex components [2, 3]. The error sources mainly include the pose error of the machining system, the kinematic error of the robot joints, and the positioning error under the end load of the robot, among which the pose error of the machining system is particularly prominent.

In order to reduce the pose error of the robotic machining system, extensive studies have been conducted from the perspectives of robot pose [4, 5], hand-eye pose [6, 7], workpiece pose [8, 9], and tool pose [8], and significant progresses have been made. When a robot is used as the equipment executive to perform grinding on the surface of large and complex components, the ACF, AOK, ABG, and other compliant flanges [10] are often used as the end effectors. In fact, another type of tool that uses brush roller installed at the robot end is used to improve the machining efficiency due to the larger contact area. The brush roller, however, is generally a non-standard customized tool which
Currently there are three main methods to compensate for the clamping and positioning error of tool at the end of robot: kinematic calibration methods [11–13], measurement and estimation of positional errors using laser trackers [14–17], and correction of clamping errors by force control [18–21]. Although the former two methods improve the positioning accuracy of the tool frame, the positioning error caused by the manufacturing and installation of the tool is not specifically compensated. Comparatively, the force control method is designed to compensate for positioning errors caused by the deformation of the tool spindle stiffness at the end of the robot, but it is not suitable for compensation of positioning errors in tools with large spindle stiffness and dimensions.

Based on this, a model for calculating the angular misalignment at the robot end brush roller-workpiece contact interface is proposed based on the elastic contact force perception. The model is verified based on ABAQUS analysis and grinding experiment, which effectively simplifies the complex calculation process encountered by the existing methods. By virtue of this method, the precise positioning of the robot end brush roller helps enhance the machining contour accuracy and surface quality of large and complex components.

### 2 Problem description

When the robot is used for grinding the surface of large-scale components, it is a common way of perceiving and controlling contact forces by an external force-controlled sensor, so as to obtain the desired surface quality and contour accuracy [22, 23]. In the machining process, the ideal contact state between the brush roller and the workpiece is shown in Fig. 1(a). However, when the brush roller behaves clamping and positioning errors, the angular misalignment at the brush roller-workpiece contact interface occurs as shown in Fig. 1(b). Moreover, slight elastic deformation is generated at the brush roller-workpiece contact interface under the action of force due to the flexible robotic machining system. In the subsequent force control machining, the under-cutting and over-cutting phenomena occur owing to the unevenly stressed surface, which increases the unevenness and roughness of the workpiece surface, and makes the workpiece to be scrapped seriously.

### 3 Calculation model of the angular misalignment at brush roller-workpiece contact interface

#### 3.1 Analysis of the elastic contact force between brush roller and workpiece

When the brush roller at the end of the robot initially contacts with the workpiece surface, the contact interface will be elastically deformed due to squeezing, thereby resulting in certain deformation volume. The elastic deformation process follows Hooke’s law. This paper describes a macroscopic contact force problem based on the bulk compressive modulus formula $K = \frac{E}{3(1-2\nu)}$, which is given by [24]. From the initial state, if the pressure increases by $\Delta P$, the volume decreases by $\Delta V$; then, there is $K = \Delta P/(\Delta V/V_0)$, and $K$ is called the bulk modulus of the object and $V_0$ is the original volume of the object. When the contact force on the brush roller and the workpiece is an interaction force, the pressure on the two is also equal, and the following formula is established.

$$\frac{K_1 \Delta V_1}{V_1} = \frac{K_2 \Delta V_2}{V_2} = \Delta P \tag{1}$$

where $K_1$ and $K_2$ are the bulk modulus of brush roller and workpiece, $\Delta V_1$ and $\Delta V_2$ are the elastic deformation volume of brush roller and workpiece, $\nu_1$ and $\nu_2$ are the Poisson’s ratio of brush roller and workpiece, and $V_1$ and $V_2$ are the original volume of brush roller and workpiece.

To simplify the calculation, it is assumed that the sum of the elastic deformation volume of the brush roller and workpiece is $\Delta V = \Delta V_1 + \Delta V_2$. Substituting it into Eq. (1), it yields:

$$\frac{K_1 K_2}{K_1 V_2 + K_2 V_1} \Delta V = \Delta P \tag{2}$$
In the elastic contact deformation, when the stiffness of the brush roller is much smaller than that of the workpiece, the elastic contact area $A$ can be approximated to a semi-ellipse, as shown in the shaded part in Fig. 2(a); then, it has:

$$A = \pi ab / 2$$  \hspace{1cm} (3)

where $a$ and $b$ are the long and short semi-axes of the semi-ellipse in the contact area, $L$ is the length of the brush roller busbar in the elastic deformer, $R$ is the brush roller radius, and $\alpha$ is the deflection angle between the brush roller and the workpiece surface.

Then according to the pressure and pressure formula $P = F/S$, the positive pressure of the contact interface, that is, the elastic deformation contact force of the brush roller can be expressed as:

$$F = \Delta PA = \frac{K_1 K_2}{K_1 V_2 + K_2 V_1} \Delta VA$$  \hspace{1cm} (5)

In the robot end tool coordinate system as shown in Fig. 2(a), the origin is located at the midpoint of the generatrix of the brush roller, and $X$, $Y$, and $Z$ represent the tangential, axial, and normal directions. For the actual elastic deformation between the brush roller and the workpiece, $\Delta x_{i\text{max}}$ is the maximum amount of deformation in a certain section in the elastic deformation volume, and $\beta_{i\text{max}}$ is the angle between the critical deformation point and the maximum deformation point in a certain section of the elastic deformation volume. As can be seen from the front view of Fig. 2(b), when the actual contact boundary between the brush roller and the workpiece is CP, the green part CMP in Fig. 2(b) is the elastic deformation volume of the brush roller, and the red part CNP is the elastic deformation volume of the workpiece; then, switch to the three-dimensional main view in Fig. 2(a), the sum of the deformation volumes of the brush roller and the workpiece is the partial volume ABCM of the cylinder. A mathematical method is used to integrate the cross-sectional area in Fig. 2(c) from the axial direction of the brush roller, which aims to calculate the elastic deformation volume:

$$\Delta V = \int_0^L \beta_{i\text{max}} R^2 - (R - \Delta x_{i\text{max}})^2 \tan \beta_{i\text{max}} dL$$  \hspace{1cm} (6)

Combining Eqs. (3), (5), and (6), the elastic contact force $F$ by the brush roller can be expressed as:

$$F = \frac{K_1 K_2 ab}{2(K_1 V_2 + K_2 V_1)} \int_0^L \left[ \beta_{i\text{max}} R^2 - (R - \Delta x_{i\text{max}})^2 \tan \beta_{i\text{max}} \right] dL$$  \hspace{1cm} (7)

Furthermore, it can be seen from the geometric relationship in Fig. 2:

$$\beta_{i\text{max}} = \left| \cos^{-1} \frac{R - \Delta x_{i\text{max}}}{R} \right|$$  \hspace{1cm} (8)

$$\Delta x_{i\text{max}} = L_i \tan \alpha$$  \hspace{1cm} (9)

where $L_i$ is the micro-element length of the generatrix length $L$ of the brush roller in the elastic deformation body.

### 3.2 Determination of the material property parameters of brush roller material

The brush roller is composed of an aluminum alloy core, an external non-woven fabric, and silicon carbide abrasive grains on the surface of the non-woven fabric. In order to improve
the calculation accuracy, the actual model of the brush roller is simplified according to the classic calculation formula of Young’s modulus to obtain the combined elastic modulus $E_1$ of the brush roller [25].

$$E_1 = (F/S)/(d_{l1}/r_2)$$

(10)

Poisson’s ratio refers to the absolute value of the ratio of the lateral strain to the axial strain when the material is under tension or compression in one direction $v = -\varepsilon_x/\varepsilon_l$. Thus, the combined Poisson’s ratio $v_1$ of brush rollers can be written as:

$$v_1 = (d_{l1}/r_2)/(d_{lx}/D)$$

(11)

As shown in Fig. 3, when the brush roller is subjected to positive pressure $F$, the lateral elastic deformation is the sum of the elastic deformation produced by both the aluminum alloy core and the non-woven fabric.

$$d_{l} = d_{l1} + d_{l2}$$

(12)

Because the axial elastic deformation is very small, it is assumed that the axial composite deformation of the brush roller is equal to the axial deformation of the aluminum alloy core and the non-woven fabric.

$$d_{l} = d_{l1} = d_{l2}$$

(13)

According to the Young’s modulus calculation formula, the definition of Poisson’s ratio, and the geometric relationship in Fig. 3, the elastic modulus $E_1'$, $E_2'$ and Poisson’s ratio $v_1'$, $v_2'$ of aluminum alloy core and non-woven fabric can be written as:

$$E_1' = \left(F/r_1^2\right)/(d_{l1}/r_1)$$

(14)

$$E_2' = (F/A)/(d_{l2}/(r_2 - r_1))$$

(15)

$$v_1' = (d_{l1}/r_2)/(d_{l1}/D)$$

(16)

$$v_2' = (d_{l2}/(r_2 - r_1))/d_{l2}/D$$

(17)

where $E_1'$ is the elastic modulus of the aluminum alloy core, which is taken as 70 GPa, and $E_2'$ is the elastic modulus of polypropylene, the raw material of non-woven fabrics, which is taken as 1.35 GPa. $v_1'$ is the Poisson’s ratio of the aluminum alloy core, which is 0.3, and $v_2'$ is the Poisson’s ratio of the polypropylene, which is 0.42. Under positive pressure, the contact area between the brush roller and the workpiece is $A$, and the area where the pressure acts on the surface of the aluminum alloy core is $r_1A/r_2$. The amount of lateral elastic deformation of the aluminum alloy core and non-woven fabric under the positive pressure are $d_{l1}$ and $d_{l2}$. and $d_{l}$ is the combined lateral elastic deformation of brush roller. The amount of axial deformation of the aluminum alloy core and non-woven fabric are $d_{l1}$ and $d_{l2}$, and $d_{l}^x$ is the combined axial deformation of brush roller $r_1$ is the radius of the aluminum alloy core, which is 37.5 mm, and $r_2$ is the radius of the brush roller, which is 75 mm. $D$ is the height of brush roller.

Both Eqs. (14) and (15) are used to express the amount of lateral elastic deformation of the aluminum alloy core and the non-woven fabric, respectively, which are given by:

$$d_{l1} = Fr_2/SE_1'$$

(18)

$$d_{l2} = F(r_2 - r_1)/SE_2'$$

(19)

Deformed from Eqs. (16) and (17), the lateral elastic deformations can also be expressed as:

$$d_{l1} = d_{l1}v_1r_1/D$$

(20)

$$d_{l2} = d_{l2}v_2(r_2 - r_1)/D$$

(21)

Combining Eqs. (12), (18), and (19), then substituting them into Eq. (10), the combined elastic modulus of the brush roller is rewritten as:

$$E_1 = \frac{E_1'E_2'r_2}{E_2'r_2 + E_1'(r_2 - r_1)}$$

(22)

Combining Eqs. (12), (13), (20), and (21), then substituting them into Eq. (11), the combined Poisson’s ratio of the brush roller is rewritten as:

$$v_1 = v_1' + \frac{r_2 - r_1}{r_2}v_2'$$

(23)
Finally, the combined elastic modulus of the brush roller is determined as \( E_1 = 2.559 \text{ Gpa} \). And the Poisson’s ratio of the brush roller is calculated to be 0.36.

### 3.3 Estimation and compensation of the angular misalignment at contact interface

During the robotic grinding process, the contact force on the brush roller is the resultant force of the normal, axial, and tangential forces measured by the force sensor. When estimating the angular misalignment at the brush roller-workpiece contact interface, the tangential force is perpendicular to the contact force that causes the elastic deformation; thus, it is not involved in the calculation and can be ignored. Therefore, the elastic contact force \( F \) is considered the vector sum of the normal force \( F_n \) and the axial force \( F_a \) measured by the force sensor.

\[
\vec{F} = F_n + F_a
\]  \hspace{1cm} (24)

According to the axial force \( F_a \) on the brush roller detected by the force sensor, both the contact force \( F \) and the normal contact force \( F_n \) caused by the angular misalignment of the brush roller can be calculated by trigonometric functions:

\[
F_n = F_a / \tan \alpha
\]  \hspace{1cm} (25)

\[
F = F_a / \sin \alpha
\]  \hspace{1cm} (26)

Due to the uneven distribution of the normal force acting on the contact surface, the resultant force is not at the midpoint of the brush roller generatrix; thus, a torque \( T_n \) around the \( X \) axis will be generated, as shown in Fig. 4. The relationship between the torque \( T_n \) and the distance \( L' \) from the force action point to the bottom end of the brush roller is given by:

\[
T_n = F_n \times \left( \frac{D}{2} - L' \right)
\]  \hspace{1cm} (27)

where \( D \) is the length of the brush roller generatrix.

Due to the linear relationship between the brush roller and the workpiece in elastic contact, the cross-sectional shape of the elastic deformation body is a right-angled triangle distribution as shown in Fig. 4. Taking the right-angle side at the resultant normal force’s action point as the boundary, the areas of the two parts \( S_1 \) and \( S_2 \) of the right-angle triangle are equal. There is the following relationship between the contact length \( L \) of the brush roller-workpiece and the distance \( L' \) from the action point of the resultant normal force to the bottom end of brush roller.

\[
L' = \frac{2 - \sqrt{2}}{2} L
\]  \hspace{1cm} (28)

The brush roller-workpiece contact length \( L \) can be expressed as:

\[
L = \frac{D - 2|F_a|}{|F_a|/\tan \alpha}
\]  \hspace{1cm} (29)

Combining Eqs. (7), (8), (9), and (29), the calculation model of the angular misalignment at the brush roller-workpiece contact interface is given by Eq. (30).

\[
\int_0^\alpha \frac{\pi \tan \alpha}{2\sqrt{2}} 2R \left[ \cos^{-1} \left( \frac{R - L_1 \cdot \tan \alpha}{R} \right) \right] \left[ R^2 \cos^{-1} \left( \frac{R - L_1 \cdot \tan \alpha}{R} \right) \right] dL_1 = \frac{2(K_1V_2 + K_2V_1) \cos \alpha}{K_1K_2} \sqrt{\left( F_a / \sin \alpha \right)^2 + F_a^2}
\]  \hspace{1cm} (30)

where both \( F_a \) and \( T_n \) can be directly measured by the six-dimensional force sensor, and only the deflection angle \( \alpha \) is unknown. Taking \( F_a \) and \( T_n \) as the input and the deflection angle \( \alpha \) as the output, the relationship between input and output of the model under different contact lengths \( L \) is shown in Fig. 5.

To compensate for the angular misalignment at the brush roller-workpiece contact interface, the rotation direction of \( \alpha \) is determined by the direction of the axial force \( F_a \), as shown in Fig. 6. If \( F_a \) is less than zero, rotate the robot end tool coordinate system clockwise around the \( X \) axis by an angle \( \alpha \) to compensate for the angular misalignment at the brush roller-workpiece contact interface. Otherwise, rotate it counterclockwise.
The commercial CAE software ABAQUS is used to simulate and verify the above contact force model. The finite element simulation model corresponding to the theoretical model is shown in Fig. 7. Note that the positioning contact between the brush roll and the workpiece is used. The workpiece material is 6005A-T6 aluminum alloy, with the dimension of 300 mm × 100 mm × 2 mm, and the generatrix height of the brush roller is 240 mm.

Owing to the high mesh accuracy required for the micro-contact simulation calculation, only the yellow part in Fig. 7(a) is calculated during the simulation to enhance the simulation speed and efficiency, as shown in Fig. 7(b). The material property parameters of the brush roller and workpiece are listed in Table 1. A completely fixed operation is adopted on the non-working surface of the brush roller and the workpiece to simulate the actual situation. Also the deflection angle is artificially set to make a small elastic contact between the brush roll and the workpiece. The simulation results are the contact pressure and torque on the contact surface.

4 Simulation verification

The simulation takes the generatrix center on the surface of the brush roller as the rotation center, and misalignment angles of 0.1°, 0.2°, 0.3°, 0.4°, and 0.5° are set for analysis. Both the axial contact pressure CFN3 and the torque around the X axis in the output of the simulation result history are used as the input of the theoretical model; then, the misalignment angle corresponding to the elastic deformation is calculated for model inverse verification. Five sets of simulation results are shown in Fig. 8 and Fig. 9, respectively. Table 2 compares the simulation results and the output data of the theoretical model.

It can be seen from the contact stress CPRESS cloud in Fig. 8 that the cross-sectional distribution of the contact

Table 1 Material property parameters of the brush roller and workpiece

| Parameter | Brush roller | Workpiece |
|-----------|--------------|-----------|
| $E$       | 2.559 GPa    | 70 GPa    |
| $\nu$     | 0.36         | 0.3       |
force is an isosceles triangle with the Y axis as the midline. This result is consistent with the calculation of the contact force in the theoretical model described above. Furthermore, the symbol cloud diagram of the reaction force RT in Fig. 9 shows that the longitudinal cross-sectional distribution of the contact reaction force is a right triangle. This result is consistent with the calculation of the contact force in the above theoretical model. These results validate the correctness of the elastic contact force analysis between the brush roll and the workpiece.

Table 2 indicates that the misalignment angle required for the simulation is smaller compared to the angular misalignment output from the theoretical model under the same conditions. This is mainly because the contact area simplified as the surface area of the deformed part of the brush roller is smaller than the actual contact area in the theoretical modeling process. The stiffness of the brush roller is much smaller than that of the workpiece; hence, the results by the theoretical model and the finite element simulation calculation are not the same. The average relative error between the simulated and theoretical values is 15.1%, which is within an acceptable range.

5 Experimental verification and result discussion

The experimental platform of robotic grinding and brushing of high-speed rail body is built, as shown in Fig. 10, which mainly includes a six-degree-of-freedom ABB industrial robot (IRB 6700–200/2.6) with an end load capacity of 200 kg, the repeated positioning accuracy is 0.05 mm, and the trajectory repetition accuracy is 0.06 mm. An F/T sensor (ATI Omega 160) is installed at the end of the sixth axis of the robot to measure contact force and torque. And the detection accuracy of the F/T sensor is shown in Table 3. The tool is a non-standard customized brush roller with a diameter of 150 mm and a height of 240 mm, which is mainly made
of aluminum alloy as the core material, and the outer layer is a non-woven fabric with silicon carbide abrasive. The workpiece is a 3 m × 2 m high-speed rail body-in-white side wall (6005A-T6 aluminum alloy), and the thickness of the aluminum alloy plate is 3 mm.

Before the experiment, the tool coordinate system is calibrated by the “four-point method” that comes with the robot operating system, and the “three-point method” is used to complete the calibration of the workpiece coordinate system [8]. After calibration, two vertical machining paths are

| Table 3 | The resolution parameters of the F/T sensor (ATI Omega 160) |
|---------|-------------------------------------------------------------|
| F/T     | Fx/Fy(N) | Fz(N) | Tx/Ty(Nm) | Tz(Nm) |
| Resolution ratio | 1/4  | 1/2  | 1/20 | 1/40 |

Fig. 9 Symbol diagram of the contact reaction force with different misalignment angles

Table 3 The resolution parameters of the F/T sensor (ATI Omega 160)

Fig. 10 Experimental platform of robotic grinding and brushing of high-speed rail body
planned under the constant force control mode with a normal force of 5 N to ensure the contact between brush roller and workpiece and to avoid the damage of the brush roller to the workpiece. When the brush roller does not rotate, the robot completes the first path movement. As shown in Fig. 11, the contact forces and torques on the brush roller are detected by the ATI force control sensor during robot operation. According to the model input requirement, the data in the middle 1/2 representing the axial force and the torque around the X axis are extracted; then, the average values are calculated as $F_a = -0.0162 \text{ N}$ and $T_n = 0.2900 \text{ N m}$. These values are input into the calculation model of angular misalignment at brush roller-workpiece contact interface, and the compensated angle is finally calculated as $0.232^\circ$.

Before the robot performs the second machining path, the brush roller is rotated clockwise around the X axis to compensate the misalignment angle of $0.232^\circ$ through the robot controller RAPID program control instruction. During the machining process, the optimal parameter combination determined by large amount of process tests [26] is selected: the brush roller speed of 11.8 m/s, the workpiece feed speed of 10 mm/s, and the normal force of 20 N. Finally, thirty times of grinding and brushing operations are performed to facilitate the measurement of experimental results.

When the machining operation is completed, the machined surface of the high-speed rail body is scanned by a PowerScan-Pro-2.3 M scanner (measuring accuracy $\pm 0.02 \text{ mm}$) to obtain spatial point cloud data, so as to quantitatively analyze the depth of material removal after grinding and brushing. Due to the limitations of the scanner single-frame photo range and the quality of the entire point cloud, the scanned results are selected separately within the Imageware software for one $160 \times 60 \text{ mm}$ equally spaced measurement range on each machining path, as shown in Fig. 12. The measurement results are represented as a chromatogram, where the horizontal coordinate indicates the horizontal direction of the machining area, the vertical coordinate indicates its vertical direction, and the color indicates the material removal depth. The point cloud data at three horizontal positions on each path are selected for further analysis, and the relevant data are shown in Figs. 13 and 14.

Figure 13 shows that the material removal depth in the machined area without angular misalignment compensation is not uniform, and the color gradient varies significantly. The problem of excessive removal at one end and insufficient removal depth at the other also exists. Specifically, the pre-machining reference of the rail body shown in position 1, position 2, and position 3 constitutes an obvious angle with the spatial point cloud data after machining, respectively. After data processing and calculation, the three included angles are $0.167^\circ$, $0.179^\circ$, and $0.192^\circ$, and the average value is $0.179^\circ$.

In contrast, Fig. 14 shows that the color distribution of the machining areas after angular misalignment compensation is more uniform, and the included angles at position 1, position 2, and position 3 are $-0.034^\circ$, $-0.021^\circ$, and $-0.018^\circ$, respectively. The average value is only $-0.024^\circ$, indicating that the depth of material removal is relatively uniform, and the contour accuracy after grinding and brushing has been improved significantly.
6 Conclusion

The angular misalignment caused by the clamping and positioning errors of the non-standard customized brush roller is a challenging task facing the robotic grinding of large-scale components. In this paper, a calculation model of the angular misalignment at the brush roller-workpiece contact interface is proposed to address the problem based on the elastic contact force perception. The following conclusions are achieved:

(1) Calculation of the misalignment angle at the robot end brush roller-workpiece contact interface needs to comprehensively consider the geometrical force relationship between the brush roller and the workpiece at the initial contact, and to determine the combined elastic modulus and Poisson’s ratio of the brush roller.

(2) When the angular misalignment is determined by taking the axial force and normal torque as input parameters of the model, rotating the corresponding angle of the brush roll by means of a robot controller RAPID program command can rapidly compensate for the clamping and positioning error of the brush roller.

(3) By comparing the simulation and theoretical values, the minimum error under the condition of brush roller-workpiece misalignment angle of 0.1 – 0.5° is only 0.03°, and the average relative error is 15.1%. The compensated angle is reduced to 0.024° from the average of 0.179° before compensation, and the depth of material removal becomes more uniform.

Author contribution Xiaozhi Feng: conceptualization, investigation, writing—original draft, writing—review and editing, methodology. Rui Lv: methodology, validation, writing. Chen Qian: methodology, writing—reviewing and editing. Yudi Wang: investigation, writing—reviewing and editing. Linli Tian: methodology, writing—reviewing and editing. Dahu Zhu: funding acquisition, writing—reviewing and editing.

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Declarations

Ethics approval The research contents of the article do not violate ethics.

Consent to participate The research does not involve human participants or animals, and the authors warrant that the manuscript fulfills the ethical standards of the journal.

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