Statistical law of variable curvature characteristics on the inside profile of the vole’s clawed toes

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Abstract. The statistical law of inside profile curves data points which vole’s clawed toes had been analyzed. The least squares method was used to analyze the inside profile curves data points for fitting mathematical model and fitting curves were expressed by polynomial equations. The statistical law of the vole’s clawed toes shows that: from the end of toes’ bodies to the tiptoes at the clawed toes, there are four extreme points which changes alternately two times, that is, there are two maximum points and two minimum points, and the abscissa of each extreme point is very concentration, near the first extreme (minimum) point was taken as the base point, the second extreme (maximum) point is located near the 43.36% of the clawed toe’s abscissa, and the third extreme point (minimum) is located near the 73.49% of the clawed toe’s abscissa. According to the curvature statistics of four extremes, the extremum points of the curvature are more concentrated except for the third extreme point (minimum). From the macroscopic morphology view of the each curvature trendline, the each curvature trendline has obvious fluctuation characteristics, the curvature trendline of the posterior left thumb and the anterior right thumb are most obvious, the curvature trendline of the posterior right index finger is relatively small. This study are contributive to revealing the intrinsic geometric characteristics of voles’ clawed toes contact with soil surface, and directing the efficient and energy-saving design of soil tillage components with similar functions.

1. Introduction

In the process of farming or earthwork construction, soil-tool suffer resistance when the soil be cut, crushed, flipped, or moved and at the same time consume a lot of energy [1]. It have always been paid much attention to improve the structure form and decrease the resistance and energy consumption of soil-tools by researchers.

Various novel anti-adhesion and resistance reduction methods have been developed based on the structural features and the working conditions of the soil-tools components by many scholars at home and abroad [2], such as vibration method [3], magnetization method [4], heating-up techniques [5], etc. However, these methods have been limited due to cannot meet the requirements of the engineering practices. Bionics is a frontier interdisciplinary subject with rapid development and wide application, involving materials science [6], biological [7], physics [8] and other related disciplines. After the long-term interactions with the living surroundings, biological organisms have evolved special body configurations highly adaptable to the living environments. It has been found that the claws of some soil animals, especially those with efficient abilities to dig and loosen earth, such as mole cricket [9], mouse...
[10] and ground squirrel [11], have special geometrically curve shapes and wedge-shape structures. This provides an idea for the bionic optimization design of the soil-tool [12].

2. Geometric prototype and analysis method of clawed toes

2.1. The inside profile of the vole’s clawed toes. There are 9 vole’s clawed toes were selected in the experiment, as shown in Figure. 1. The pictures of each clawed toe were amplified and placed in the Cartesian coordinates, and the end of each clawed toe should be coincided with the coordinate origin [13]. In addition, in order to facilitate the observation and comparison, each clawed toe’s inside profile curves from the end to the tiptoes are placed in the fourth quadrant of the Cartesian coordinates, the positive direction of the horizontal coordinate points to the tiptoe, as shown in Figure. 2.

![Figure 1. Picture of vole’s clawed toes.](image)

![Figure 2. Cartesian coordinates of Figure. 1(a)](image)

2.2. Mathematical model of the inside profile curves. The least squares method was used to fit the inside profile curves data points of the vole’s clawed toes. It was verified by experiments that the four polynomial has a higher fitting precision, and its expression is:

\[ f(x) = a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0. \] (1)

| Clawed toe’s name                  | \( a_4 \)   | \( a_3 \)   | \( a_2 \)   | \( a_1 \)   | \( a_0 \)   | \( R^2 \) |
|-----------------------------------|------------|------------|------------|------------|------------|---------|
| (a) posterior right index finger  | 1.2092*10^{-8} | -1.3448*10^{-5} | 0.0067     | -1.7832    | 0.2077     | 0.9995  |
| (b) posterior right middle finger | -7.1625*10^{-9} | -2.483*10^{-6} | 0.0051     | -1.7051    | -2.2409    | 0.9987  |
| (c) posterior left index finger   | -4.7486*10^{-8} | 1.6227*10^{-5} | 0.0011     | -1.01      | 2.0193     | 0.9991  |
| (d) posterior left middle finger  | 4.9376*10^{-8} | -4.1923*10^{-5} | 0.0145     | -3.2688    | 3.2622     | 0.9997  |
| (e) posterior left thumb          | -1.6192*10^{-7} | -3.189*10^{-6} | 0.016      | -3.2494    | -20.1612   | 0.9994  |
| (f) anterior right thumb          | -8.1621*10^{-8} | -3.5538*10^{-6} | 0.0128     | -2.8176    | -3.9573    | 0.9951  |
| (g) anterior right index finger   | -4.2804*10^{-8} | 2.5378*10^{-8} | 0.0074     | -2.0375    | 5.1963     | 0.9984  |
| (h) anterior right middle finger  | 1.1609*10^{-8} | -1.5291*10^{-5} | 0.0086     | -2.5563    | 0.0872     | 0.999   |
| (i) anterior left middle finger   | 1.9302*10^{-8} | -2.0646*10^{-8} | 0.0069     | -2.4042    | -4.2978    | 0.9972  |
According to the polynomial of each fitting curve to calculate the curvature of each point on the curve, and drawing the curvature trendlines of the inside profile curves, as shown in Figure 4.

3. Discuss

3.1. Statistical law of curvature trendlines’ changes. As can be seen from Figure 4, the law of curvature trendlines’ changes as follows: the curvature trendlines obtain a minimum point at the end of toes’ body, it is gradually increased to a maximum point when inside profile curves transition to the tip part, and then gradually reduced to second minimum point, finally, it is increased to second maximum points, that is, it contains two maximum points and two minimum points. In order to further study the geometric features of inside profile curves of each clawed toes, the four extreme points of the curvature trendlines are identified as A, B, C, and D points in turn, as shown in Figure 5.
3.2. Statistical law of data eigenvalues. In order to facilitate observation and analysis, the abscissas of the four extreme points A, B, C, and D are respectively defined as $x_a$, $x_b$, $x_c$, and $x_d$, the curvature values of the four extreme points are defined as $k_a$, $k_b$, $k_c$, and $k_d$. According to the abscissas of the three extreme points B, C and D, the abscissas ratio of point B and C to point D is calculated respectively, which are defined as $x_b/x_d$ and $x_c/x_d$, then the statistical eigenvalues of each data are obtained, as shown in Table 2.

![Figure 5. Schematic diagram of curvature trendline](image)

| Name                                      | $x_b$(mm) | $x_c$(mm) | $x_d$(mm) | $x_b/x_d$ | $x_c/x_d$ |
|-------------------------------------------|-----------|-----------|-----------|-----------|-----------|
| (a) posterior right index finger          | 120       | 275       | 370       | 0.3514    | 0.7027    |
| (b) posterior right middle finger         | 150       | 269       | 371       | 0.4528    | 0.7682    |
| (c) posterior left index finger           | 116       | 191       | 263       | 0.4297    | 0.7338    |
| (d) posterior left middle finger          | 103       | 207       | 283       | 0.3604    | 0.735     |
| (e) posterior left thumb                  | 88        | 124       | 161       | 0.5528    | 0.7702    |
| (f) anterior right thumb                  | 104       | 151       | 195       | 0.5385    | 0.7692    |
| (g) anterior right index finger           | 107       | 170       | 215       | 0.4884    | 0.7907    |
| (h) anterior right middle finger          | 171       | 317       | 469       | 0.3625    | 0.6823    |
| (i) anterior left middle finger           | 137       | 255       | 385       | 0.3662    | 0.6623    |
| minimum value                             | 88        | 124       | 161       | 0.3514    | 0.6623    |
| maximum value                             | 171       | 317       | 469       | 0.5528    | 0.7907    |
| range value                               | 83        | 193       | 308       | 0.2014    | 0.1284    |
| average value                             | 121.78    | 217.67    | 301.33    | 0.4336    | 0.7349    |
| median                                    | 116.00    | 207.00    | 283.00    | 0.4297    | 0.7349    |
| standard deviation                         | 24.76     | 61.01     | 97.15     | 0.0748    | 0.0418    |
| coefficient of variation                  | 20.33%    | 28.03%    | 32.24%    | 17.24%    | 5.69%     |

The coefficient of variation ($x_b/x_d$ and $x_c/x_d$) are all small as described in Table 2, it also shows that the relative positions of the extremum points B and C are relatively concentrated for different clawed toes. In addition, because the coefficient of variation of $x_c/x_d$ is less than the $x_b/x_d$, this shows that $x_c/x_d$ is less discrete than $x_b/x_d$.

3.3. Statistics law of extreme point eigenvalues. Calculating the curvatures of four extreme points, A, B, C, and D respectively, defined as $k_a$, $k_b$, $k_c$, and $k_d$, as shown in Table 3.

| Name                                      | $k_a$(1/mm) | $k_b$(1/mm) | $k_c$(1/mm) | $k_d$(1/mm) |
|-------------------------------------------|--------------|--------------|--------------|--------------|
| (a) posterior right index finger          | 0.001568     | 0.003318     | 0.002116     | 0.003358     |
| (b) posterior right middle finger         | 0.001321     | 0.004628     | 2.69E-05     | 0.005674     |
As can be seen from table 3, the $k_a$ has the smallest coefficient of variation, $k_c$ have the largest coefficient of variation. The coefficient of variation for $k_b$ and $k_d$ is between $k_a$ and $k_c$, and the coefficient of variation is close to $k_a$. This also shows that the curvature of the three extreme points (A, B and D) are relatively concentrated, the curvature of the C point is more scattered, this is consistent with the macroscopic observations in Figure 4.

4. Summary

(a). The inside profile curves of the vole’s clawed toes showed complex variable curvature characteristic, the curvature get a minimum point at the end of all clawed toes’ bodies, it is gradually increased to a maximum point when inside profile curves transition to the tip part, and then gradually reduced to second minimum point, finally, it is increased to second maximum points, that is, it contains two maximum points and two minimum points.

(b). The abscissa of the extreme points B and C are relatively concentrated for different clawed toes, the concentration degree of the minimum point C is higher than maximum point B.

(c). The curvature of the three extreme points (A, B and D) are relatively concentrated, the curvature of the C point is more scattered.

(d). The characteristic of variable curvature of the vole’s clawed toes inside profile curves made vole possessed outstanding abilities of digging, reducing resistance and anti-adhesion against soil. Footnotes should be avoided whenever possible. If required they should be used only for brief notes that do not fit conveniently into the text.

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