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Geometrical features and wettability of dung beetles and potential biomimetic engineering applications in tillage implements

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Abstract

Dung beetles can break up dung pads and compact dung into balls and their cuticle surfaces do not stick dung or soil. The geometrical features of some dung beetles and wetting behavior of the pronotum cuticle surfaces of the dung beetle *Copris ochus* Motschulsky were investigated. It was found that dung beetles have embossed textured surfaces on their pronotum, clypeus and elytra. The head of dung beetles have shapes similar as bulldozing blades. The forelegs of dung beetles have a tooth-like structure with strong burrowing ability. The number and/or the size of the teeth of the forelegs are dependent upon the species of dung beetles. The pronotum surface profiles of the tested dung beetle *C. ochus* Motschulsky displayed approximately a statistical fractal character and the estimated fractal dimension of the pronotum surface profile was 1.877. The wetting tests showed that the apparent contact angles of water on the pronotum surface of the dung beetle *C. ochus* Motschulsky were 91–106.5° and the average contact angle was 97.2°, representing a hydrophobic property. Some potential engineering applications of the geometrical features of dung beetles and the wetting behavior of their cuticle surfaces in biomimetic designs of tillage implements were discussed.

Keywords: Dung beetle; Cuticle surface; Geometrical feature; Wettability; Biomimetics; Tillage implement

1. Introduction

Tillage is still an important farming operation although the conservative tillage has been developed and extended more and more extensively. The reduction of the energy consumption due to the tillage resistance is paid attention to and the effective energy-saving techniques for tillage implements are being researched by agricultural engineers. The forward resistance of the tillage implements is mainly resulted from the soil cutting (shearing) resistance, the soil friction resistance, and the resistance due to soil adhesion as well. A heavy soil adhesion and friction will increase the energy consumption considerably and decrease the working quality of tillage implements. For examples, the forward resistance of moldboard plow is increased due to soil adhesion and friction and the emergence rate of seeds is seriously decreased due to adhesion of soil to such implements of sowing machines as the furrowing opener and components for covering soil. Soil animals have been adapted to the soil surroundings. Two different adaptations for soil have occurred in soil-burrowing animals, the passive adaptation and the active adaptation. The passive adaptation of soil

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animals to the soil habitat resulted in shorter or vestigial additional legs, the body becoming smaller, thinner or flatter, and wings and eyes diminishing. The stronger digging legs were a result of active adaptation for burrowing (Xin, 1986).

Dung beetles, a kind of soil animal (insect), have a function of cleaning up pasture. Most dung beetles share the habit of feeding on the dung of mammals. Some of them feed on compost. Most dung beetles can break up dung pads by means of the shovel-like clypeus and compact dung into balls using their stout forelegs. The dung balls are rolled away from the dung mass and buried in nest in the soil as food. Horgan (2001) evaluated the quantities of cow dung buried by dung beetles (Coleoptera: Scarabaeidae). People acknowledge the contribution of dung beetles to improve the pasture ecosystems and soil quality. The biological characters and behavior have mainly been focused on the research of dung beetles and other beetles. For examples, Kim and Leal (2000) studied the ultrastructure of pheronmone-detecting sensilla placodea; Emlen and Nijhout (1999) examined the hormonal regulation of horngrowth of the dung beetle *Onthophagus taurus*; Hunt and Simmons (2002) revealed the behavioral dynamics of biparental care in the dung beetle *O. taurus*. Some researchers carried out the research of the structure of the exoskeleton of beetles. Gunderson and Schiavone (1989) demonstrated that the insect exoskeleton has evolved for a variety of demanding duties. The microscopic examination showed that the bessbeetle cuticle is a composite material consisting of layered plies having fiber orientations that alternate in a dual helicoidal pattern. There are varying geometry and size of the reinforcing fibers in the different position of the ply. Chen et al. (2002) also observed the microstructure of Hydrophilidae cuticle, discovered the structural feature of several unique plies and designed a composite laminate with holes similar as the beetle cuticle. This biomimetic composite laminate possessed markedly high strength as compared to the composite laminate with a normally drilled hole.

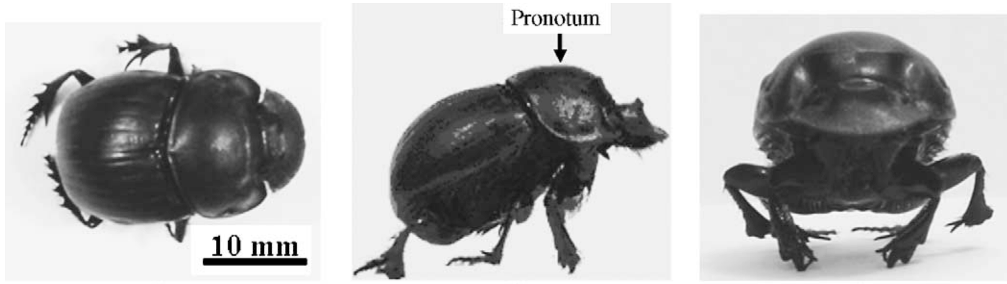
Some characters of soil animals including dung beetles have been carried out by researchers in terrain machine research field as their body surfaces have the excellent anti-adhesive and anti-resistant property (Ren et al., 2001a; Tong et al., 1994a). Several biomimetic methods to reduce the forward resistance against soil were developed on the basis of the anti-resistant principles of soil animals, such as the biomimetic non-smooth surfaces (Qaisrani et al., 1992; Ren et al., 1995) and biomimetic electro-osmotic systems for soil-engaging surfaces (Ren et al., 2001b). The observation of dung beetles showed that their body surfaces do not stick soil and moist dung during cutting dung from dung pads and burrowing tunnels in soil. The geometrical features of some dung beetles and wettability of the dung beetle *Copris ochus* Motschulsky were examined and analyzed and their potential biomimetic engineering applications in tillage implements were discussed in this work.

2. Materials and methods

Some living dung beetles, *C. ochus* Motschulsky, were collected in the suburb of Changchun, Jilin Province, China. Figs. 1 and 2 are photographs of one male and one female dung beetle *C. ochus* Motschulsky, respectively. Their body was about 25 mm in length and about 16 mm in width. The dung beetles

(a) (b) (c)

Fig. 1. Digital camera photographs of the male dung beetle *C. ochus* Motschulsky: (a) top view; (b) side view; (c) front view.



(a) (b) (c)

Fig. 2. Digital camera photographs of the female dung beetle *C. ochus* Motschulsky: (a) top view; (b) side view; (c) front view.

collected were swashed using distilled water and then fixed for 12 h in the solution with ethanol of 70 wt.%. The whole body images of dung beetle *C. ochus* Motschulsky shown in Figs. 1 and 2 were taken with a digital camera. The geometrical morphologies of the dung beetle *C. ochus* Motschulsky were examined with a stereoscope (XTJ-30) and a scanning electron microscope (JXA-840).

The surface profiles of the pronotum of the dung beetle were examined using a 3D-SRAT-1 type of profiler with a stylus of 2 μm radius tip. The middle area of the pronotum was selected for measuring the profile. The length for each sampling was 0.25 mm and 2000 data were sampled in the total sampling length of 2.5 mm. One profile along *x*-direction (longitudinal direction of the body) was measured every 122.2 μm along *y*-direction (transverse direction of the body). Thirty-one profiles along *x*-direction were, totally, measured at the different positions in *y*-direction.

Female dung beetle shown in Fig. 2 was used for measuring the contact angles. The contact angles of water on the pronotum surfaces were determined at 20 °C by the sessile drop method (Joel, 1994) with a contact angle measuring instrument (JC2000A). The sessile drop method is an effective method to determine the contact angles of liquid on solid surfaces. A drop of liquid was put on the pronotum cuticle surface using a micro-syringe. Then the angle between the liquid–solid interface and the tangent of the liquid–gas interface arc were measured at the three-phase intersection using a microscope. Fig. 3 illustrates the schematic diagram of the measuring positions on the pronotum cuticle surface for the contact angles measurement.

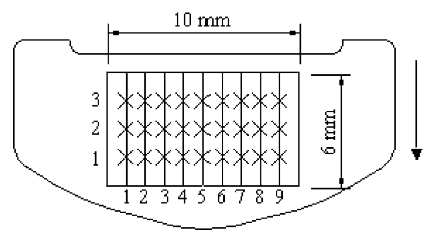


Fig. 3. Schematic diagram showing the measuring positions on the pronotum for contact angles (the direction of arrowhead is from head to cauda, that is, *x*-direction).

The related research results of some dung beetles and a desert beetle by other researchers were referenced for the comparative analysis of the geometrical morphologies with the dung beetle *C. ochus* Motschulsky.

3. Results

3.1. Geometrical morphologies of dung beetle

Dung beetles belong to the family Scarabaeidae. Their body consists of the prosoma (head), mesosoma (thorax, including elytra and abdomen) and metasoma. Both male and female dung beetle *C. ochus* Motschulsky have a blade-like head and one horn on the head, as shown in Figs. 1 and 2. The pronotum of the male dung beetle *C. ochus* Motschulsky is very different from the pronotum of the female in geometrical configuration.

The stereoscopy showed that a embossed texture surface with many small convex domes was evolved on the cuticle of the pronotum and clypeus of both the male and the female dung beetle *C. ochus* Motschul-

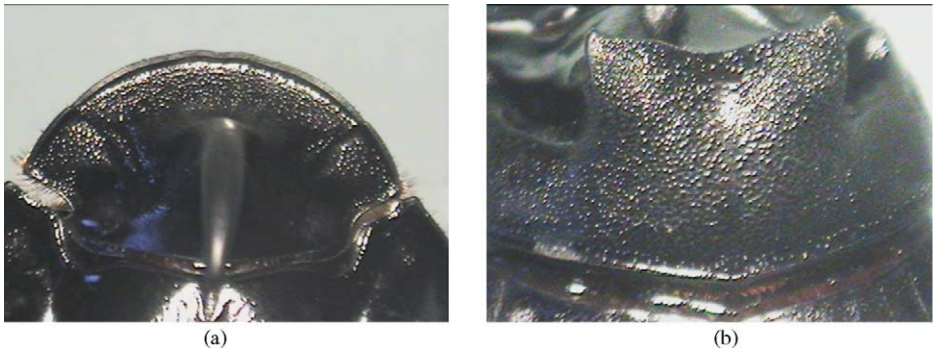


Fig. 4. The cuticle surface details of the clypeus and pronotum of the male dung beetle *C. ochus* Motschulsky: (a) clypeus; (b) pronotum (stereoscopy photographs).

sky, as shown in Figs. 4 and 5(a). Fig. 5(b) is a scanning electron microscopy photograph showing the detail of the convex domes on the pronotum of the dung beetle. It can, obviously, be observed from Fig. 5(b) that many micro-cracks are there between the convex domes on the pronotum of the dung beetle.

Figs. 6 and 7 illustrate the morphologies of the forelegs, midlegs and hindlegs of the male and female dung beetle *C. ochus* Motschulsky, respectively. The two forelegs of the dung beetle *C. ochus* Motschulsky are fossorial ones with tooth-like shape, offering a very stout burrowing function to soil or dung. The midlegs and hindlegs are very different from the forelegs in tarsal claw structure.

3.2. Fractal and wettability of the pronotum of C. ochus Motschulsky

If $z(x)$ is a profile of a rough surface along x-direction, the power spectrum of the profile is

$$P(\omega) = \frac{1}{L}\left|\int_0^L z(x)\exp(\mathrm{i}\omega x)\,\mathrm{d}x\right|^2 \tag{1}$$

where $P(\omega)$ is the power of a wave of frequency ω, L is the sampling length. Then, its structure function $S(\tau)$ is

$$\begin{aligned} S(\tau) &= \langle (z(x) - z(x+\tau))^2 \rangle \\ &= \int_{-\infty}^{\infty} P(\omega)(\mathrm{e}^{\mathrm{i}\omega\tau} - 1)\,\mathrm{d}\omega \end{aligned} \tag{2}$$

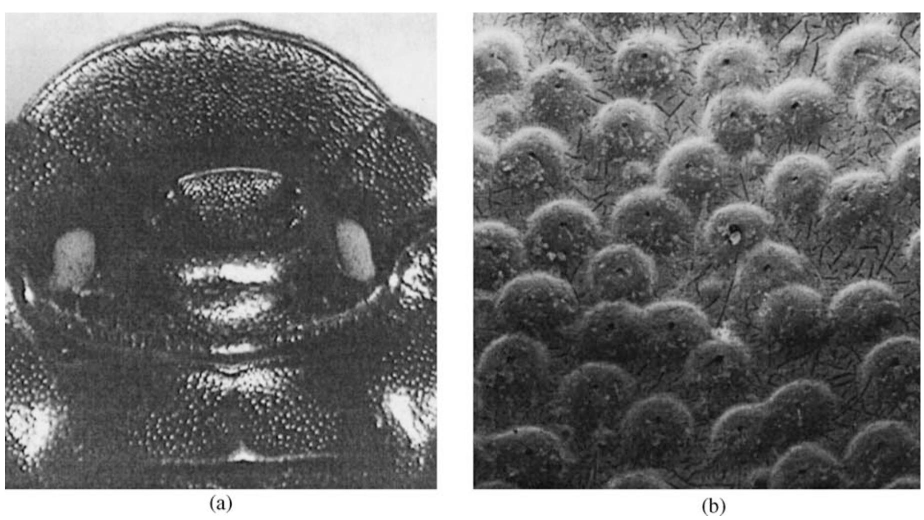


Fig. 5. The cuticle surface details of the cuticle of female dung beetle *C. ochus* Motschulsky. (a) Stereoscopy image of the clypeus and pronotum; (b) scanning electron microscopy image of the convex domes on the pronotum.

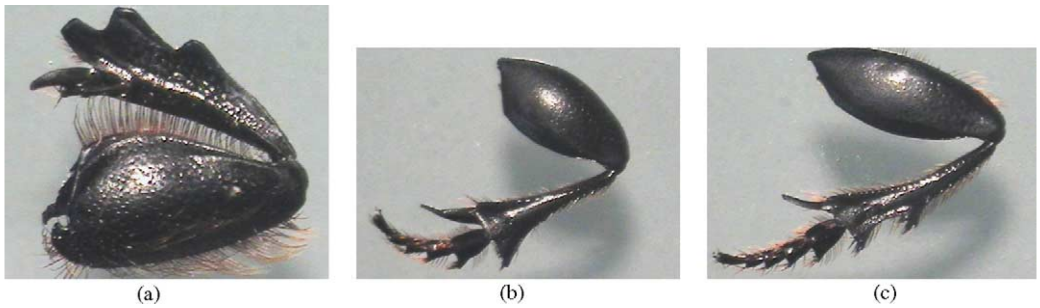


Fig. 6. Digital camera photographs of legs of the male dung beetle *C. ochus* Motschulsky: (a) foreleg; (b) midleg; (c) hindleg.

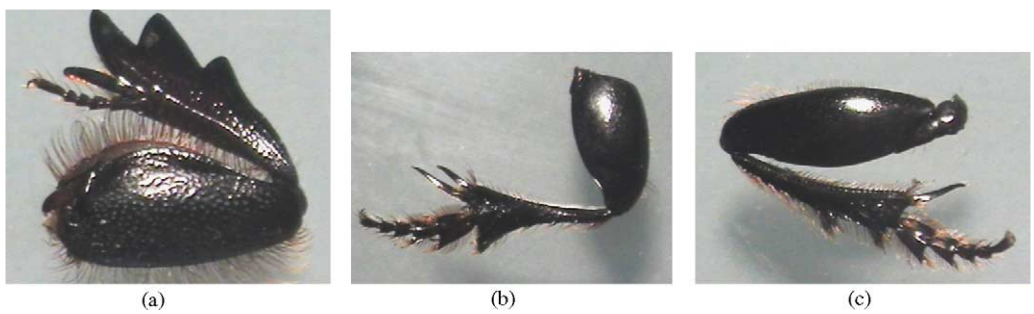


Fig. 7. Digital camera photographs of legs of the female dung beetle *C. ochus* Motschulsky: (a) foreleg; (b) midleg; (c) hindleg.

where τ is the measure, $\langle \cdots \rangle$ means spatial averaging. For a fractal profile, the fractal dimension of the profile can be estimated by the relation of the structure function $S(\tau)$ with measure τ (Bhushan and Majumdar, 1992):

$$S(\tau) \propto \tau^{4-2D} \tag{3}$$

A program for estimating the fractal dimension of the pronotum of the dung beetle *C. ochus* Motschulsky was designed based on the structure function method and the measured 31 profiles along x-direction of the pronotum surface were analyzed.

Fig. 8 shows the morphology measured by the stylus profiler. It was found that all the measured profiles displayed the approximate linear relation of log–log of $S(\tau)$ with τ. Fig. 9 shows the log–log relationship of $S(\tau)$ with τ for the measured fifth profile of the pronotum of the dung beetle *C. ochus* Motschulsky. Table 1 lists the results of the estimated fractal dimensions of 31 profiles of the pronotum of the dung beetle. The estimated fractal dimensions of the 31 profiles of the pronotum cuticle surface were very close, indicating an approximately self-similar fractal feature. The average fractal dimension (D) of the 31 profiles of the pronotum cuticle surface was 1.877. The interval of the fractal characteristic feature of the pronotum profile was from 2.6878 to 148.44 μm. So, the surface fractal dimension (D_s) of the pronotum of the dung beetle was $D_s = D + 1 = 2.877$, suggesting that the pronotum surface was rough in the measuring scale since the average fractal dimension of the surfaces was close to 3.

Fig. 10 shows the contacting state of a distilled water drop on the pronotum cuticle surface of the dung beetle *C. ochus* Motschulsky. Table 2 lists the mea-

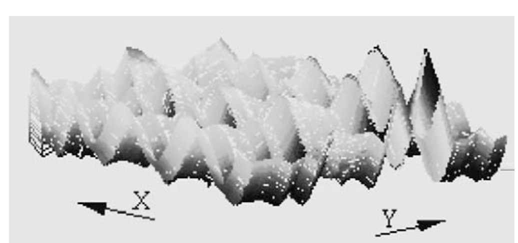


Fig. 8. The texture of the pronotum surface of the dung beetle *C. ochus* Motschulsky measured by a profiler.

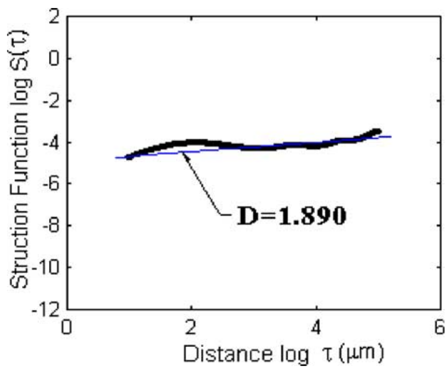


Fig. 9. Relationship of $\log S(\tau)$ with $\log \tau$ for a profile of the pronotum cuticle surface of the dung beetle *C. ochus* Motschulsky.

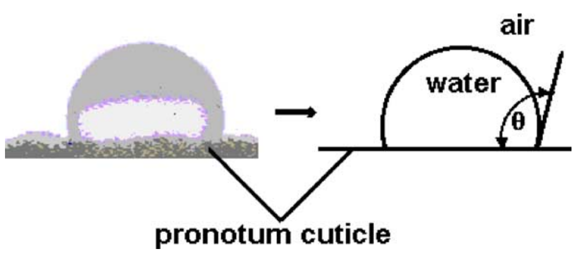


Fig. 10. The contact state of water sessile on the pronotum cuticle surface of the dung beetle *C. ochus* Motschulsky.

sured contact angles of water on the pronotum cuticle surface, corresponding to the measuring positions shown in Fig. 3. The contact angles of water on the pronotum cuticle surface were in between 91° and 106.5° and their average value was 97.2°, indicating a hydrophobic property of the pronotum cuticle surface.

Table 1
The estimated fractal dimensions (*D*) of the profiles along the *x*-direction of the pronotum surface of the dung beetle *C. ochus* Motschulsky at the varied *y*-direction positions

Positions	*D*	Positions	*D*
1	1.896	16	1.777
2	1.892	17	1.891
3	1.890	18	1.896
4	1.891	19	1.901
5	1.890	20	1.889
6	1.900	21	1.901
7	1.895	22	1.897
8	1.893	23	1.874
9	1.896	24	1.892
10	1.881	25	1.874
11	1.864	26	1.897
12	1.878	27	1.889
13	1.762	28	1.891
14	1.889	29	1.895
15	1.722	30	1.895
		31	1.889

4. Discussion

4.1. Geometrical features of dung beetles

As far as geometrical structure was concerned, the head of dung beetles can be considered as a natural bulldozing shovel and the clypeus of the head as blade, as shown in Figs. 1, 2 and 11. The horizontally projected profile of the outside line of the clypeus of the dung beetle *C. ochus* Motschulsky, male or female, is approximately a parabola and the profile of the clypeus is at the same envelope curve with the hor-

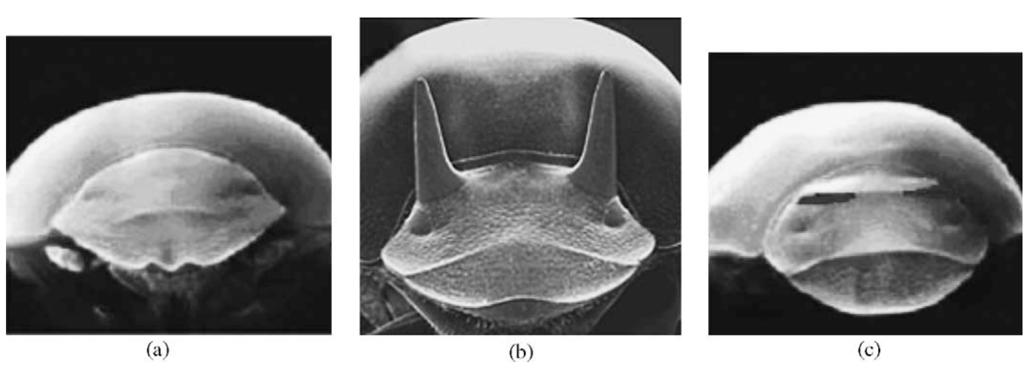


Fig. 11. The morphology of the head of dung beetles (from Emlen, 2001). (a) *Onthophagus sharpi*, female; (b) *Onthophagus* species from Ecuador, male; (c) *Onthophagus* species from Ecuador, female.

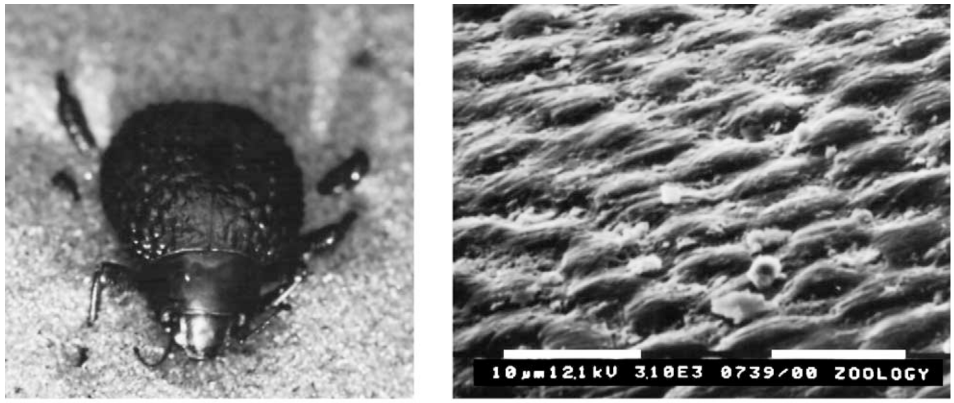
Table 2
The measured results of the contact angles (°) of water on the pronotum cuticle surface of the dung beetle *C. ochus* Motschulsky

x-Direction	*y*-Direction								
	1	2	3	4	5	6	7	8	9
1	96.1	91.6	102.7	97.5	92	91.5	97.5	96.2	100.1
2	96.1	100.2	91.6	101.7	100.6	92	106.5	104.9	98.8
3	91.5	93.9	91.2	95.4	106	91	97.2	99.1	101

izontally projected profile of the pronotum and elytra, as shown in Figs 1(a) and 2(a). The clypeus of *Onthophagus* is, to some extent, different from *C. ochus* Motschulsky in structure. The clypeus cuticle surface consists of two curved surfaces and there is a ridge between the both surfaces, as shown in Fig. 11(a)–(c). The clypeus with a blade-like shape is often used for breaking dung of mammals. When the dung becomes a ball, the dung beetle often put its head down to the ground and rolls the dung ball using its midlegs and hindlegs into caves burrowed in soil. There exist some striaes on the surfaces of the elytra of dung beetles as shown in Figs. 1(a) and 2(a). Almost dung beetles produce one or more horns on head or/and thorax. Male and female dung beetle *C. ochus* Motschulsky produce one horn on their heads and the horn of the male dung beetle *C. ochus* Motschulsky is much longer than that of the female. As the difference between them in the horn morphology, their heads and the pronotum front are very different in morphology, comparing Figs. 1(c) and 2(c). Emlen (2001) examined the structural features of horns of three species of dung beetle *Onthophagus* and demonstrated that there were different number of the horns and different arrangement patterns. The number, location and the size of the horns had, obviously, effect on the size of neighboring morphological structures (antennae, eyes, or wings) and the relative horn size was negatively correlated with the relative size of the nearest neighboring structure.

It can, obviously, be observed from Fig. 5(b) that many micro-cracks are there between the convex domes on the pronotum of the dung beetle *C. ochus* Motschulsky. Prins (1986) studied some South African dung beetles. The illustrations of the South African dung beetles showed the similar morphologies of the embossed cuticle surface structure on the pronotum and clypeus of *Onthophagus cameloides*, *Epirinus flagellatus*, *Copris anceus*, *Neateuchus proboscideus* and *Trox fascicularis* as *C. ochus* Motschulsky. The similar cuticle surface geometry can be seen on the head cuticle of dung beetle *Onthophagus* species from Ecuador as shown in Fig. 11(b) (Emlen, 2001) and on the head cuticle of a bronze dung beetle *Onitis alexis* as shown in Fig. 12. The pronotum and clypeus cuticle surfaces of dung beetles often contact very sticky wet dung of mammals or wet soil, but adhesion phenomenon of dung or soil to those surfaces do not occur. This indicates that the pronotum and clypeus cuticle surfaces of dung beetles possess high anti-adhesive ability against wet dung and soil. Besides dung beetles, almost other beetles have rough (not smooth) cuticle surfaces, such as, ground beetles, tiger beetles, whirligigs, predacious diving beetles, wrinkled bark beetles, scarabs, stag beetles and rain beetles. Parker and Lawrence (2001) demonstrated that the hard front wings (elytra) of the desert beetle *Stenocara* sp. are covered in bumps (convex domes) with 0.5–1.5 mm apart and each about 1.5 mm in diameter, as shown in Fig. 13(a). The peaks of these bumps are smooth and wax-free and the near-by sloping sides and depressed areas are rough and covered

Fig. 12. *O. alexis* (bronze dung beetle). http://www.ento.csiro.au/Ecowatch/Primary/beetles/beetles_index.htm.



(a) (b)

Fig. 13. An adult female desert beetle *Stenocara* sp. (a) Adult female desert beetle *Stenocara* sp. showing the geometry covered in bumps on its wings (elytra); (b) scanning electron microscopy morphology (SEM) image of the depressed areas (supplied by Dr. Andrew R. Paker).

with wax. Fig. 13(b) illustrates the rough microstructure consisting of flattened hemispheres of a diameter of 10 μm with a regular hexagonal array.

The legs of insects are divided into ambulatorial (walking) legs, saltatorial legs, raptorial leg, fossorial (digging) legs, natatorial legs, clasping legs, scansorial legs and cordiculate legs according to their functions. The legs of dung beetles have, certainly, a walking function. The two forelegs of the dung beetle *C. ochus* Motschulsky are fossorial ones with tooth-like shape, offering a very strong burrowing function to soil or dung. This was the results of the active adaptation of dung beetles for the living surroundings. All the dung beetles have such two forelegs suiting for burrowing in soil. The morphological difference of the forelegs among different species of dung beetles is in the number, shape and size of the teeth, as shown in Figs. 7(a), 8(a) and 12. This difference was also seen in the illustrations of some South African dung beetles reported by Prins (1986) and in the related internet address. For the dung beetle *C. ochus* Motschulsky, between the forelegs of the male and female are there a certain difference. The teeth of the forelegs of the female *C. ochus* Motschulsky are sharp and the teeth of the male are obtuse, comparing the illustrations in Figs. 6(a) and 7(a). The midlegs and hindlegs of the dung beetle *C. ochus* Motschulsky are very different from its forelegs in shape, especially, in their tarsal claw structure. The midlegs and hindlegs are mainly used for walking, holding and clasping. For example, the dung beetle often puts its head down to the ground and rolls dung ball to move using their hindlegs and midlegs, indicating the holding and clasping action.

4.2. Hydrophobic property of the dung beetle cuticle surfaces

A birds' feather and many plants had effective water-proof surfaces. Barthlott and Neinhuis (1997) analyzed the self-cleaning property of the biological surfaces of some plants. Some plants had microscopically smooth surfaces, such as, beech *Fagus sylvatica* L., evergreen trees *Gnetum gnemon* L. and *Magnolia grandiflora* L., and rainforest herb *Heliconia densiflora* Verlot. Some plants had rough water-proof surfaces, such as, kohlrabi *Brassica oleracea* L., taro *Colocasia esculenta* (L.) Schott., the petal of a composite *Mutisia decurrens* Cav. and the sacred lotus *Nelumbo nucifera* Gaertn. It was demonstrated that the water-proof property of plant surfaces is dependent upon the roughness and the intrinsic wettability of the plant surfaces. The contaminated particles on the water-proof plant surfaces can be removed completely by water droplets, that is, the water-proof plant surfaces can causes an almost complete surface purification. Barthlott and Neinhuis (1997) called the self-cleaning effect the "Lotus-Effect". There exists a similar effect for the pronotum cuticle surface of the dung beetle *C. ochus* Motschulsky as the Lotus-Effect. If assuming the contour of the rough surface of the pronotum cuticle is a wave form profile, the apparent contact angle θ_a for the waveform surface can be expressed as

$$\cos\theta_a = r\cos\theta_0 \tag{4}$$

where θ_0 is the intrinsic contact angle of the surface substance and r is the roughness factor. In fact, r is the ratio of the actual surface area to the apparent surface area. According to Eq. (4), the apparent contact angles for solid surfaces whose intrinsic contact angles are more than 90° could be elevated due to the existence of the surface roughness. While, the apparent contact angles for solid surfaces whose intrinsic contact angles are less than 90° could be declined due to the existence of the surface roughness. The contact angle of water of 91–106.5° on the pronotum cuticle surface indicated that the roughness of the pronotum surface could elevate its hydrophobic property. Wagner et al. (1996) identified the relationship between the wing microstructures of 97 insect species, their wettability of water on the wing cuticle surfaces and their behavior under the influence of contamination. It was found that the wing cuticle surfaces of some insects showed a hydrophilic property (that is, the contact angle with water was less than 90°) and the wing cuticle surfaces of some insects else showed a hydrophobic property (that is, the contact angle with water was more than 90°). Some insects with strong hydrophobic wings had a very significant self-cleaning effect under the influence of rain or dew.

If the roughness and the fractal feature of the solid surfaces extend to the molecular scale, Eq. (4) cannot predict the apparent contact angles of liquid on these surfaces. Hazlett (1990) derived an equation for apparent contact angles for these solid surfaces. The expression of θ_a for liquid 1 on molecular fractal surfaces is

$$\cos\theta_a = \left[\left(\frac{1-\Gamma f^{1-D_s/2}}{1-\Gamma}\right)\left(\frac{\sigma_1}{\sigma_R}\right)^{1-D_s/2}\right]\cos\theta_0 \tag{5}$$

where $\Gamma \equiv (\gamma_{s2}/\gamma_{s1})$, $f \equiv (\sigma_2/\sigma_1)$, γ_{s1} is the interface tension of solid with liquid 1, γ_{s2} is the interface tension of solid with liquid 2, σ_1 is the molecular cross-sectional area of fluid 1, σ_2 is the molecular cross-sectional area of fluid 2, σ_R is the molecular cross-sectional area of a fluid by which the solid surface area measured equals its projected area, θ_0 is the intrinsic contact angle of liquid 1 on the solid surface substance, and D_s is the molecular fractal dimension of the solid surface. The first term between brackets on the right-hand side of Eq. (5) is a wettability factor r_w, $r_w = (1-\Gamma f^{1-D_s/2})/(1-\Gamma)$, depending Γ, f and D_s. If $\Gamma < 1$ and $f > 1$, or $\Gamma > 1$ and $f < 1$, then the wettability factor increases with D_s, while, if $\Gamma > 1$ and $f > 1$, or $\Gamma < 1$ and $f < 1$, then the wettability factor decreases with D_s. The second term between brackets on the right-hand side of Eq. (5) is a roughness factor r_r, $r_r = (\sigma_1/\sigma_R)^{1-D_s/2}$, which always increases with the fractal dimension D_s of the solid surfaces. For a solid–water–air three-phase system, fluid 1 is water, $\sigma_1 = 0.108\,\text{nm}^2$, and fluid 2 is air mainly consisting of nitrogen and oxygen. The covalent radii of nitrogen and oxygen molecules are 7.3 and 7.4 nm, which are very near. So, it can be considered that air consists of nitrogen only and, so, $\sigma_2 = 0.162\,\text{nm}^2$. Therefore, $f \equiv (\sigma_2/\sigma_1) = 0.162/0.108 = 1.5$, that is, $f > 1$. If the solid is a high surface energy material, then $\gamma_{s2} < \gamma_{s1}$ and $\Gamma \equiv (\gamma_{s2}/\gamma_{s1}) < 1$, so, r_w decreases with D_s. However, if the solid is a low surface energy material, such as the pronotum surface, $\Gamma \equiv (\gamma_{s2}/\gamma_{s1})$ is less than 1 and r_w increases with D_s. Therefore, an increase of the fractal dimension of a solid surface possessing an intrinsic hydrophobic property is to further enhance its hydrophobic property.

4.3. Potential biomimetic applications in tillage implements

The forward resistance of soil tillage implements is affected by the soil-cutting (shearing) resistance, the soil friction resistance and the resistance due to soil adhesion. Soil adhesion will exist when soil is in touch with a solid surface because of the capillary attraction force and the viscous resistance of the water film between soil and the solid surface (Tong et al., 1994b). Friction between soil and a solid surface and the abrasive wear of the solid material by soil will take place when the solid surface slides against soil. Adhesion, friction and abrasive wear against soil are the main soil-related tribological phenomena occurring in soil-engaging implements and have various effects on the working quality and energy consumption of the implements.

Hydrophobic function of the cuticle surfaces of dung beetles indicates that the cuticle is a low surface energy material. The rough texture existing on the pronotum surface of the dung beetle *C. ochus* Motschulsky could enhance the hydrophobic function. The combination of the hydrophobic function and rough texture is the main reason why dung beetles' cuticle surfaces do not stick dung, soil and water, similar to the "Lotus-Effect" of many plant surfaces (Barthlott and Neinhuis, 1997). The lotus leaf possesses a very dense layer of epicuticular wax with high hydrophobic property and displays a textured surface consisting of the distinctively convex to papillose epidermal cells. The combination of the surface roughness caused by different microstructures together with the hydrophobic properties of the epicuticular wax causes an extremely reduced adhesion of water as well as particles on the lotus leaf.

The information from the textured cuticle surface morphologies and hydrophobic character provide a clue to develop anti-adhesion and anti-friction techniques for the soil-engaging surfaces of tillage implements against soil. The test results of the relationship between soil adhesion and wettability of several solid surfaces showed that the high surface energy materials, such as metals and inorganic nonmetals, possessed high adhesion force and friction resistance against soil and the low surface energy materials, such polymers as ultra high molecular weight polyethylene (UHMWPE) and its composite materials, polytetrafluoropolyethylene (PTFE), polyethersulfone–PTFE possessed lower adhesion force and friction resistance against soil (Liu et al., 1998; Tong et al., 1994b, 1999).

The structural characters of the cuticle surfaces of the pronotum and the clypeus of dung beetles can be applied for the designs of the working surfaces of some soil-engaging implements. The structural feature of the pronotum and the clypeus of dung beetles was directly magnified for designing the biomimetic anti-resistant bulldozing blades and plow moldboards with the arrangement of convex domes on their working surfaces (Qaisrani et al., 1992; Ren et al., 1995; Han et al., 2001). It was shown that the biomimetic blades and plow moldboards had a lower forward resistance as compared to the conventional blades and moldboard without the convex domes. Particularly, the effectiveness of the biomimetic surfaces with the convex domes made from UHMWPE was higher than those with convex domes made from plain carbon steel because of a higher hydrophobic property of UHMWPE (Qaisrani et al., 1992).

The geometrical features of the tarsal claws of the forelegs of dung beetles would be useful in biomimetic designs of the geometrical structure of cutting blade edge and parts for breaking clods in subsoilers and cutting blade edge. Tong et al. (2003) investigated the curvature features of the claws of three soil-burrowing animals, a house mouse (*Mus musculus*), a yellow mouse (*Citellus dauricus*) and a mole cricket (*Gryllotalpidae*). It was found that these claws displayed a curved cone or pyramidal configuration and the upper outlines and the lower outlines of the claws had a complicated changing curvature. It was demonstrated by the finite element analysis by Guo (2002) that the biomimetic subsoilers modeled by the geometrical configurations of the above three soil-burrowing animals' claws had much lower forward resistance than the subsoilers with straight line, cycloid and simple parabola under otherwise identical conditions.

In conclusion, the geometrical features of dung beetles and the wetting behavior of their cuticle have some potential biomimetic engineering applications in tillage implements. The embossed textured surfaces would be used for designing the biomimetic soil-touching working surfaces of plow moldboards and furrowing openers; the geometry of leg claws would be used for designing the biomimetic curved soil cutting blades and biomimetic subsoiler; the hydrophobic property of the cuticle, particularly, the combination of the hydrophobic property and the embossed textured surfaces, would be used for development of anti-adhesive and anti-resistant composite materials or composite coatings. Some further biomimetic research is being conducted by the authors.

5. Conclusions

The authors investigated the geometrical features of some dung beetles, including *C. ochus* Motschulsky, and wetting behavior of the pronotum cuticle of *C. ochus* Motschulsky. The main conclusions are as follows.

Dung beetles had embossed texture surfaces on their pronotum, clypeus and elytra. The head of dung beetle *C. ochus* Motschulsky had a shape similar as bulldozing shovel. The forelegs of dung beetles as stout burrowing organs had a tooth-like structure and the number and the size of the teeth are dependent upon the species of dung beetles.

The profile of the pronotum cuticle surface of dung beetle *C. ochus* Motschulsky displayed approximately an statistically fractal feature, the average fractal dimension D was 1.877 and the fractal interval was from 2.6878 to 148.44 μm, suggesting that the pronotum was a rough surface in the measuring scale.

The contact angles of water on the pronotum surface of the dung beetle *C. ochus* Motschulsky were in between 91° and 106.5° and the average value was 97.2°, indicating a hydrophobic property. The rough morphology existing on the cuticle surface of dung beetles enhanced the hydrophobic function, even if the fractal feature of the pronotum surface was traced to the molecular scale.

The geometrical features of dung beetles and the wetting behavior of their cuticle have some potential biomimetic engineering applications in tillage implements, such as biomimetic plow moldboards, biomimetic furrowing openers, biomimetic curved cutting blades, biomimetic subsoiler and biomimetic composite materials or coatings in improving the anti-adhesive and anti-resistant properties.

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