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Friction properties of the head articulation in the beetle *Pachnoda marginata* (Coleoptera, Scarabaeidae)

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ABSTRACT

The head articulation of the beetle *Pachnoda marginata* is a micro-tribological system which consists of the ventral convex structure called *gula* and the corresponding concave surface of the *prothorax*. The surfaces of both parts are in contact and are expected to be optimised for friction reduction. The relationship between structure, mechanical properties of the cuticle material and friction properties of this micro-tribological system are investigated. The surface and material structure of the *gula* and its *prothoracic* counterpart were studied in fractured pieces of the cuticle using scanning electron microscopy (SEM). Friction force measurements and contact area estimations between the *gula* and a glass plate were carried out for different normal loads (0.1–10.0 mN) using two different microtribometers. The tribological behavior of the *gula* cuticle was studied on the (1) fresh, (2) dry, and (3) dry chemically (chloroform-methanol) treated samples. The dry samples exhibited a considerably rougher surface compared to the fresh ones. Furthermore, the chemical treatment led to some decrease in surface roughness. The fresh *gula* cuticle had the largest contact area and the highest friction coefficient. The drying out of the cuticle led to a decrease in both the contact area and friction coefficient. The friction coefficient was the lowest in the chemically treated *gula*, although the contact area was larger than in the dry condition. The tribological results were partly explained by direct measurements of the contact area fitted by the Hertz and JKR contact models.

1. Introduction

Any movement involving contact between two surfaces or between a surface and a medium has to deal with the resistance of the surfaces or medium. This resistance is a friction phenomenon, which is believed to have a great influence on the evolution of certain biological structures [1]. Organisms have developed different ways to save muscular energy by the use of friction-increasing and friction-reducing (anti-friction) systems. Surface counterparts in various biological joints are adapted to maximise or to minimise contact forces within joints depending on the particular function. Working principles of friction and anti-friction systems depend on mechanical interlocking, chemical properties and on the maximisation or a minimisation of the contact area between counterparts [2].

On one hand, there are attachment devices in biology having structural stability and therefore requiring high contact forces to fixate body parts to one another [1]. In this case, the pair of contacting surfaces is predefined, such as in wing-locking mechanisms of beetles [3–5] or the head-arrester system of dragonflies [1,6]. Attachment pads on legs of insects and other animals are systems where one surface is unpredictable [1]. On the other hand, some biological contact pairs which mediate body movements are specialised to reduce contact forces. These anti-friction systems mostly have a predefined pair of surfaces, like the head articulation system in beetles [7,8] or the hemelytra-hindwing sliding mechanism in bugs [9].

The head articulation of the beetle *Pachnoda marginata* is an anti-friction system [10]. A predefined, functionally corresponding pair of contacting surfaces forms a tribological system with specific structural architecture and properties. However, each contacting part has different surface texture and material structure. The rather smooth surface of the hemispherical head-part called *gula* is believed to contribute to the friction minimisation in contact with its counterpart in the concave dorsally faced part of the *prothorax* covered by asymmetric outgrowths [8]. In living condition, the organic substances on the cuticle surface,

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such as lipids and waxes are assumed to serve as lubricants to reduce friction in this biological microsystem [10].

In this paper, the relationship between friction behavior, material structure, contact area, surface roughness, hydrophobicity and mechanical properties (hardness and elastic modulus) was studied. The tribological properties of the head part (*gula*) of the articulation of the beetle *Pachnoda marginata* were tested using a microtribometer Basalt BT01 [11]. Structure of the head articulation was studied by means of computer tomography and scanning electron microscopy. The friction properties of samples prepared from the *gula* cuticle were measured in the fresh, dry and chemically treated conditions. The aim was to understand the influence of desiccation (dry) and chemical removal of the outer wax layer on tribological properties of the *gula* surface. Friction measurements and estimation of the contact area of the *gula* with a flat glass surface were carried out by a microtribometer and a micro-force tester, respectively, at different normal loads (100–10,000 μN). The results shed light on the question which features of the *gula* surface are responsible for friction reduction.

2. Material and methods

2.1. Materials and sample preparation

The beetles *Pachnoda marginata* were anesthetized with CO_2. Heads were dissected from the body and cleaned from soft tissues. The fresh *gula* was tested immediately (after 3–5 min dissecting from the body). Dry samples were obtained by drying fresh samples in an oven for 24 h at 40 °C. Chemically treated samples were prepared from the dry samples; in order to remove waxes from the surface, dry samples were washed in a solution of chloroform and methanol (2:1) for 50–60 min and air-dried for 60–90 min at room temperature.

2.2. Micro computer tomography (μ-CT)

To visualise the relative position and shapes of the contacting surfaces, the anatomy of the head articulation system of the beetle was imaged with the X-Ray μ-CT (X-Ray μ-CT system, Sky Scan 1072 at the Institut für Kunststoffprüfung (IKP), University of Stuttgart, Germany). This method allows non-invasive imaging of the internal structure of the beetle exoskeleton. The imaging was performed on air-dried samples. The images of the head articulation of the beetle were taken in two directions: transversal and sagittal (magnification × 30).

2.3. Scanning electron microscopy (SEM)

The surface structure of the *gula* and corresponding surface of the *prothorax* was studied in SEM. The samples were fixed in 2.5% glutaraldehyde in a phosphate buffer (pH = 7.3), dehydrated in an ascending row of ethanol and then critical-point dried. Pieces of the dried material were fractured using a razor blade. The prepared samples were mounted on holders, sputter-coated with gold-palladium (10 nm thickness) and examined in a SEM Hitachi S-800 at 20 kV.

2.4. Friction measurements

Friction measurements were performed using the microtribometer Basalt-BT01, which was developed for microtribological studies on biological materials (Fig. 1) [2,11]. This instrument contains a computer-controlled seven-axis precision positioning system. The head of the microtribometer can be extended over the distance of 15 mm and tilted to 90 °. The glass plate was attached to the glass double-leaf spring attached to the piezo-electric precision drive. The head was fixed on the sample holder containing rotating and tilting mechanisms.

In friction measurement, the *gula* was brought into contact with a glass plate. A normal force (F_N) was applied perpendicular to the bottom of the sample holder. The plate was sheared parallel to the sample holder and perpendicular to the direction of applied force. The tangential force (F_T) was measured from the deflection of the spring while sliding the sample along the x-axis in both directions (distal-proximal). The friction behavior of the *gula* was tested in five sliding cycles against the glass plate over the sliding distance of 100 μm. The experiments were done for seven different normal loads: 30, 100, 300, 1000, 3000, 5000 and 10,000 μN. Friction properties of 10 heads were measured in their fresh, dry and chemically treated conditions. As a control, friction properties of a sapphire ball, 1.5 mm in radius, were used. The glass plate and sapphire ball were cleaned with alcohol before each experiment.

2.5. Surface roughness measurement

The surface roughness was estimated using a white-light interferometer (Zygo New View 500, Zygo Corporation, USA), based on the information of how much the interference fringes departed from being straight and equally spaced [12]. This technique can be used to obtain the average surface roughness (R_a), the average absolute value of ten-point height (R_z) and the root mean square (*rms*) roughness of the height profile. Three heads were tested for each condition. The radius of the *gula* was obtained from the surface profile measurement using the Perthometer concept (Mahr GmbH, Göttingen, Germany). The average radius measured was 1.3 mm.

2.6. Evaluation of the apparent contact area between the gula and glass surface

The size of the apparent contact area between the *gula* and glass plate could not be obtained during the friction experiment. Therefore, a separate measurement of the contact area at different loads was necessary. The experiments were performed using the force tester consisting of a motorized micromanipulator (DC3001R with controller MS314, World Precision Instruments, Sarasota, FL, USA) and the load cell force transducer (100 g capacity, Biopac Systems Ltd., Santa Barbara, CA, USA). The same applied loads were used as those used in the friction measurements. It was rather difficult to obtain precise values of the area because of a very small size of the contact spot, especially at low loads. The error is typically about 10%.

The sample was fixed on the force transducer mounted on the micromanipulator. The load was applied by pressing the *gula* against the glass plate attached to the immobile metal stage. The load was monitored by the force transducer. The mirror was attached at 45° to the glass plate and the contact area was observed and photographed through a microscope. For each load and condition 10 heads were tested. Sapphire balls with radii of 1.5 mm and 0.5 mm were used for control measurements. The glass plates and sapphire balls were cleaned with alcohol before each experiment.

2.7. Contact angle measurement

Contact angle measurements on the head articulation of the beetle were performed using contact angle measurement device OCA 20 (Data Physics Instruments GmbH, Filderstadt, Germany). The sessile drop method was used. A microdrop (3 μl) of water was applied on the *gula* surface. The contact angle of the drop was measured from the tangent applied to the drop profile in the point of contact between air, fluid and solid material. The experiments were performed on three heads for each condition (fresh, dry, chemically treated).

3. Results

3.1. Micro-tomography

Images showing cross sections of the contact parts (*gula* and *prothorax*) of the head articulation were taken in dry insects in two

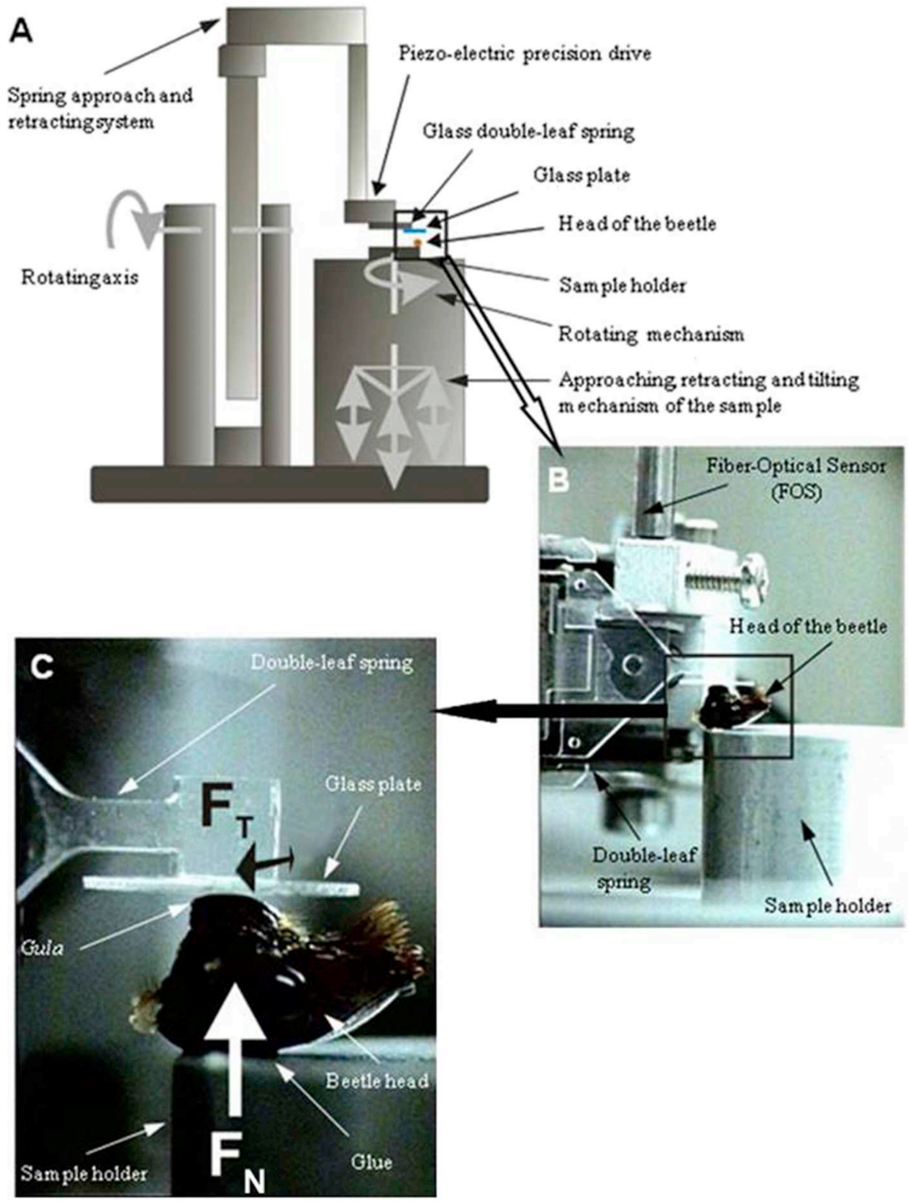

Fig. 1. Microtribometer Basalt BT01 (Tetra GmbH, Ilmenau, Germany) used in the friction measurement: A. Scheme of the experimental design; B, C. Photographs of the relative position of the *gula* to the force sensor in the friction measurement. F_N and F_T are applied (normal) and tangential (friction) forces, respectively.

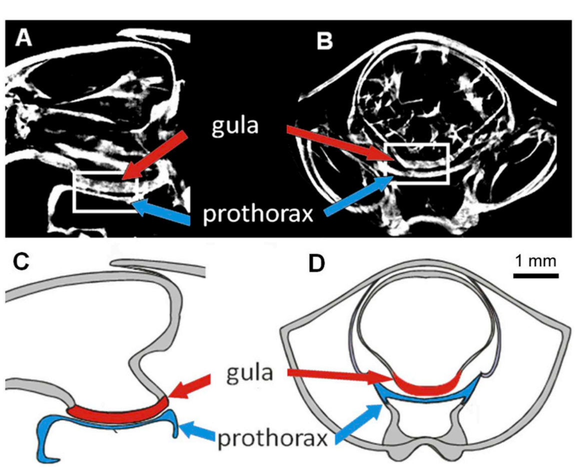

Fig. 2. μ-CT tomography images (A, B) and scheme of the joint studied (C, D) in sagittal (A, C) and transversal (B, D) planes.

directions: sagittal (Fig. 2A, C) and transversal (Fig. 2B, D). As can be distinguished from the images, the head articulation system is an open joint with a hemispherical convex shape of the *gula* cuticle (Fig. 2). Especially in the transversal images, the beetle head articulation is reminiscent of a technical ball bearing system.

3.2. Structure of the cuticle

The pores densely penetrate the relatively smooth surface of the *gula* (Fig. 3A, C). However, the *gula* surface contains a certain structure of hills and valleys with spatial wavelengths of 30–60 μm. Dry amorphous substances can be often seen on the air dried *gula* surface (Fig. 3A, C). The *prothorax* surface corresponding to the *gula* is covered by cuticular outgrowths (Fig. 3B, D). They are 20–30 μm long and are asymmetrical in shape, with the shallow slope facing medially and the steeper slope facing laterally. At the lateral side of each outgrowth, a short hair with a diameter of 5 μm is situated. These hairs contain little microtrichia pointed distally. The hairs are presumably responsible for sensory function but have not been investigated further. From μ-CT images

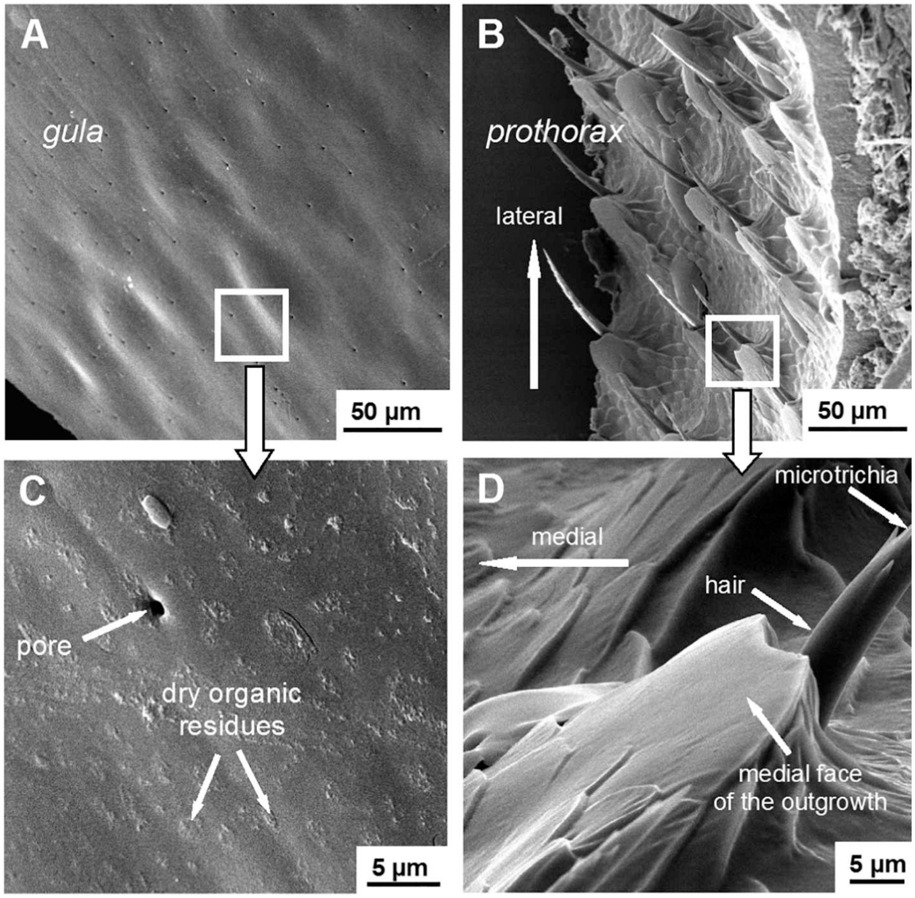

Fig. 3. SEM images of the *gula* (A, C) and *prothorax* (B, D) surfaces of the beetle. The *gula* and the *prothorax* surfaces are part of the head articulation and operate in contact. On the *gula* surface, pores and dried organic substances are presented.

showing the relative position of both *gula* and *prothorax,* one can conclude that the *gula* surface presumably contacts the shallow sides of outgrowths.

3.3. Friction properties

In Fig. 4B, the tangential force is plotted versus the sliding distance for one sample in the fresh, dry and chemically treated conditions for one cycle and at one applied normal force (5000 µN). The relationship between tangential and normal force is shown for seven different applied forces (F_N = 30, 100, 300, 1000, 3000, 5000, 10,000 µN) for the fresh, dry and chemically treated heads (Fig. 5). The tangential force increases with increasing normal load. The friction coefficient determined from the normal load F_N and the tangential force F_T (F_T/F_N) varies depending on the sample condition. Fig. 6 presents average values for 10 measurements for each condition and each applied load. Fresh heads exhibited the highest friction coefficient, whereas dry and chemically treated samples displayed much lower ones. The results also showed a decrease of the friction coefficient with increasing applied load, which is rather typical for the microtribosystems.

3.4. Surface roughness

The *gula* has hemispherical convex shape (Fig. 7). Surface profiles in fresh, dry and chemically treated conditions are different (Fig. 7). Fresh samples are rather smooth (Fig. 7A). Drying causes an increase in roughness of the *gula*-cuticle (Fig. 7B). The roughness of the chemically treated dry cuticle is slightly reduced in comparison to the dry cuticle (Fig. 7C). The average values of the surface roughness parameters R_a and *rms* are presented in Table 1.

3.5. Contact area

The contact area between the glass plate and the *gula* cuticle increased with increasing applied load (Fig. 8). There was also a strong dependence of the contact area on the sample condition. The contact area was higher for the fresh samples, followed by the chemically treated and the dry samples.

3.6. Contact angle of water

Fig. 9 presents the results of contact angle measurements for *gula* cuticles in fresh, dry and chemically treated conditions. No significant differences in contact angle for the different sample conditions were revealed.

4. Discussion

To understand the functional principle of the *gula*, the material structure, properties and tribological behavior of the *gula* were evaluated. The resulting structure-properties relationships relevant for friction minimisation in the head articulation will be discussed below.

4.1. The influence of water loss

As is known from previous studies, desiccation has a great influence on the tribo-mechanical behavior of biological systems. As a result of water loss, cuticle of the dried *gula* is substantially harder and stiffer than fresh cuticle [13]. Water is one of the essential components of the cuticle which, together with chitin, proteins and lipids, is responsible for the broad range of mechanical properties of the cuticle [14]. In the

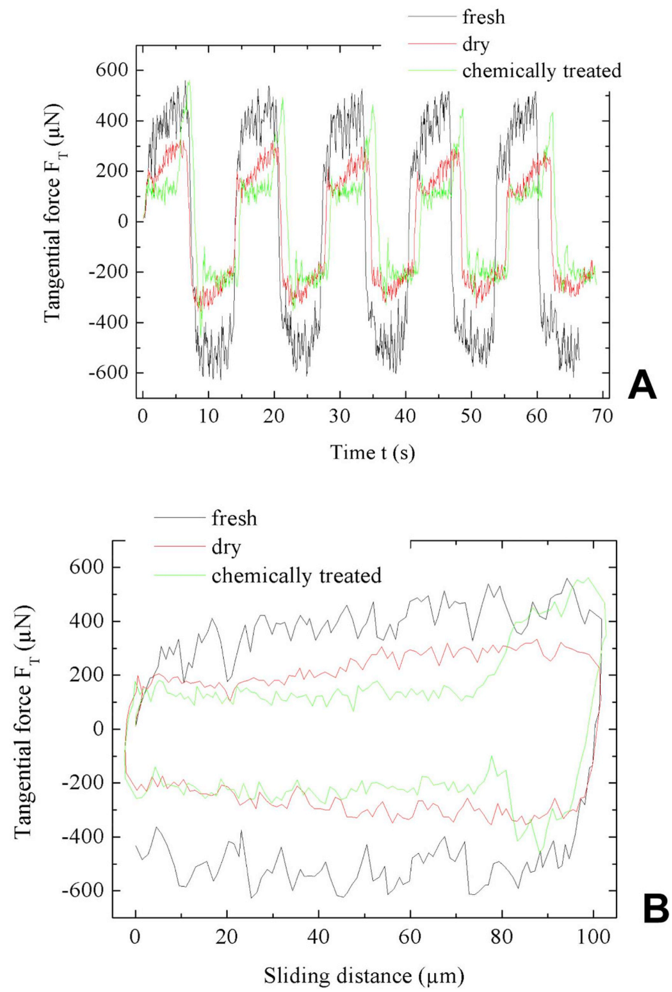

Fig. 4. Tangential force versus time (five sliding cycles per sample) (A) and versus sliding distance (one sliding cycle per sample) (B) measured in the friction experiment. The results for fresh, dry and chemically treated cuticles are shown.

fresh condition, the surface of the *gula* cuticle is also extraordinarily smooth for a biological material. The water loss is thought to cause different dimensional changes in the various cuticle layers leading to the wrinkling of the surface, which in turn increases surface roughness. That is why desiccation causes changes in the real contact area under load. In addition, soft and compliant fresh *gula* displays a larger apparent contact area at same load than the dry one: also mechanical properties of the cuticle are responsible for differences in the contact area. Due to the stiffening of the samples, the contact area of dry and chemically treated *gulas* becomes smaller in the tribological experiment.

According to Rabinowicz [15], hard and stiff materials are better for friction minimization in sliding applications than soft and compliant ones. Lower elastic modulus and lower surface roughness of the fresh *gula* are believed to be the reason for the higher friction coefficient compared to the dry *gula*.

4.2. *The influence of the lipid layer*

Insect cuticle is covered by the lipid-like layer called epicuticular grease [16,17], which was here definitely present in the fresh and presumably partially in dry samples. Washing of the dry samples in chloroform-methanol solution causes only small changes in the indentation results compared to the dry samples [14]. After chemical treatment, sample surface becomes slightly stiffer in the first 1 μm of

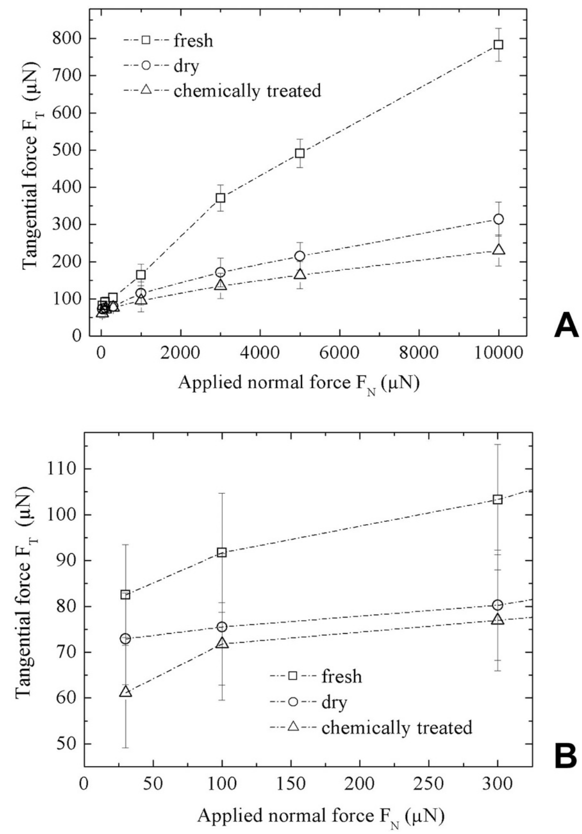

Fig. 5. Tangential force versus normal force for fresh, dry and chemically treated heads. A. All applied loads (30, 100 and 300 μN and 1, 3, 5, and 10 mN). B. Low applied loads (30, 100 and 300 μN). Each data point corresponds to the mean value obtained in 10 measurements. Scale bars are standard deviations.

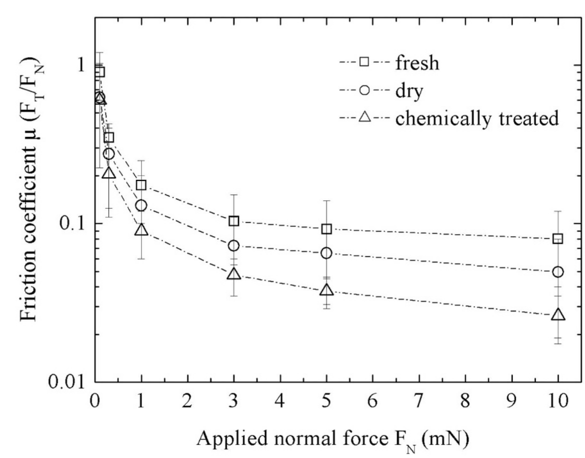

Fig. 6. Friction coefficients for fresh, dry and chemically treated *gulas* versus normal force. Mean values and standard deviations obtained in 10 measurements for each normal load and each condition (fresh, dry and chemically treated) are shown.

the indentation depth. Further stiffening of the cuticle after chemical treatment is thought to be caused by the removal of the dry organic substances, such as waxes and lipids, from the sample surface.

As was shown previously [14], the mechanical properties of the dry and chemically treated cuticle differed only insignificantly from each other. The chemical treatment reduced the surface roughness only slightly (R_a = 0.103 ± 0.008 μm, *rms* = 0.117 ± 0.011 μm). This could be caused by partial dissolution of the dry organic substances on the cuticle surface. However, the roughness of fresh samples was lower

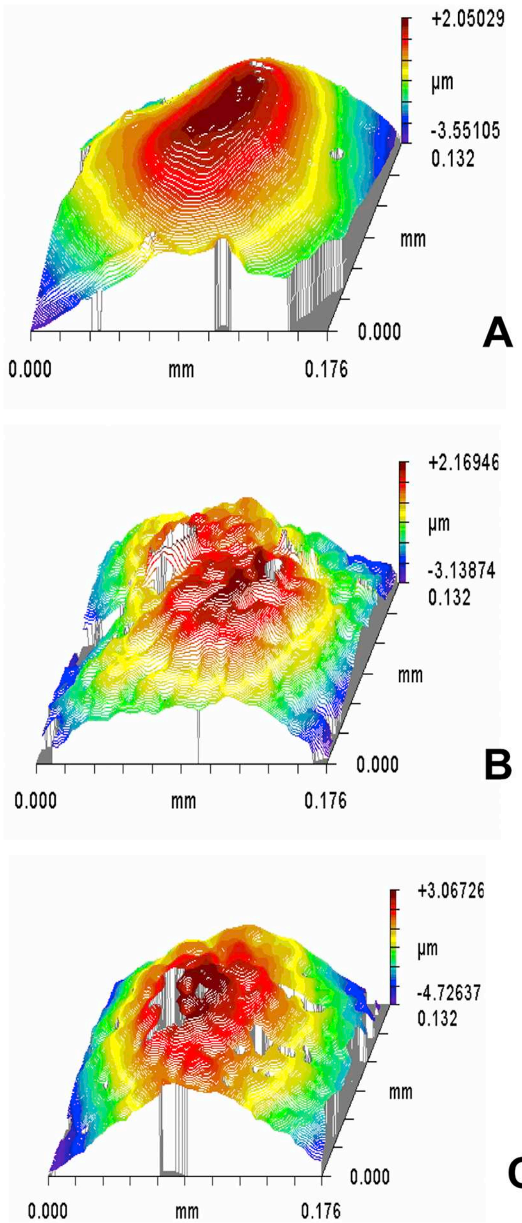

Fig. 7. The white-light interference microscopy images of surface profiles of fresh (A), dry (B) and chemically treated (C) *gulas*.

Table 1
Surface roughness parameters (*Ra, rms*) obtained by white-light interference microscopy for fresh, dry and chemically treated *gulas*. The measurements were carried out on three samples for each condition. Data represent average values and standard deviations.

Sample condition	Surface roughness parameter	
	Ra (nm)	*rms* (nm)
Fresh	33 ± 5	38 ± 7
Dry	161 ± 11	197 ± 15
Chemically treated	103 ± 8	117 ± 11

than that of dry and chemically treated ones. Because of the decrease in roughness, the contact area of chemically treated samples presumably became slightly larger at the same load than that of dry samples.

We initially assumed that the lipid-like organic substances, such as cuticular waxes on the surface would serve as lubricating agents.

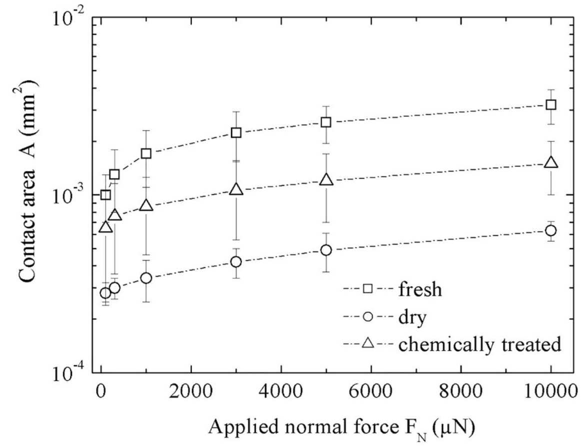

Fig. 8. Contact area in dependence on the applied force for fresh, dry and chemically treated *gulas*. 10 measurements for each applied load and each condition were performed.

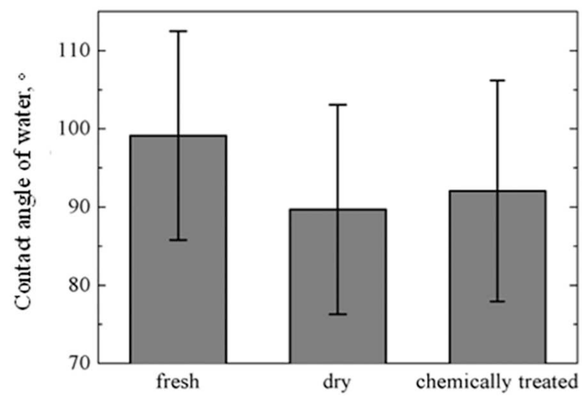

Fig. 9. Contact angles of water on fresh, dry and chemically treated *gulas*. Three samples in each condition were measured and three measurements on each sample were carried out. Data represents average values and standard deviations.

Therefore, the friction coefficient of the fresh samples was expected to be lower than that of the dry ones. A chemical treatment, which removed waxes from the sample surface, would hence have led to the highest friction coefficients. As is clearly shown in the Results section, we obtained quite different results. The following two explanations are offered. The first one is that the lubricating effect of organic substances is not strong enough within insect joints, which is of course quite different from vertebrate joints supplemented with a lubricating synovial fluid. The second explanation is that friction of the *gula* is not primarily influenced by lubrication, but by other factors, such as surface geometry, hydrophobicity and mechanical material properties [15,18–21]. In the case of fresh samples, the material has the lowest stiffness and roughness, which may lead to the formation of the highest real contact area at same load. This will result in the highest friction coefficient observed among the three types of samples.

4.3. Friction behavior of the gula cuticle

The friction behavior depends on a variety of variables of both contacting surfaces. It is determined by several different factors, such as contact area, surface energy of both contacting bodies and roughness of both surfaces [15]. The friction coefficient is calculated as.

$$\mu = \frac{F_T}{F_N} \tag{1}$$

where *FT* and *FN* are the measured tangential force and the applied normal force, respectively. Within the regime of Amontons' law (or Amonton-Kotelnikovs' law according to Borodich and Savencu [22]), the friction coefficient μ remains constant at different loads for a pair of materials and the friction force is independent of the apparent area of contact [15,22–25]. The apparent area independence means that the coefficients of friction for large and small bodies are same [15]. These classical laws of friction frequently fail, however, for the description of the tribological behavior at the micro- and nanometer scale. Friction forces are often found to strongly depend on the real contact area between the surfaces, and therefore also on microroughness, which mediates the real contact area [15,26–28]. The dependence on the real contact area is thought to be related to adhesive forces arising between the contacting surfaces [15].

Friction at the microscale is additionally influenced by surface interaction phenomena. When two bodies form contact, attractive forces of different nature may contribute to adhesion between them. The strength of adhesion depends on the surface energy of both surfaces [29]. Van-der-Waals forces, capillarity, and electrostatic forces (in the range of mN down to nN) may strongly influence the tribological behavior at low applied forces. Wettability is an important factor responsible for the formation of thin surface water film, which has a great effect on the friction behavior in the milli- and micronewton regime of loads. With an increase of the water film thickness on the surface, a meniscus is formed that may bridge single asperities and increase shear forces [30]. On hydrophobic surfaces, the formation of the water film is reduced. Under increasing applied loads, the surfaces then come closer together and the friction force increases due to adhesion caused by van-der-Waals forces.

In the presence of adhesion, the normal force F_N^* is given by

$$F_N^* = F_N + F_A \tag{2}$$

where F_A is the contribution of attraction forces and F_N applied load. Now Eq. (1) can be rewritten as

$$\mu = \frac{F_T}{F_N + F_A} \tag{3}$$

which is Coulomb law in the form suggested by Derjaguin [31].

Depending on the attractive force, friction between two ideal (molecularly smooth) surfaces can be adhesion-controlled (high attraction) or load-controlled (low attraction). Adhesion-controlled friction is proportional to the area of the real (molecular) contact. Load-controlled friction is proportional to the applied load.

Even a few nanometers of roughness can change tribological properties of contacting surfaces. The contact area, as well as mechanical properties of both materials, determines tribological properties of the tribopair. In stiff materials, an increase in roughness of one of contacting surfaces will result in smaller contact areas at the same load and, consequently, lower adhesion, which in turn results in a decrease of friction forces.

The friction behavior of the *gula* cuticle was found to be influenced not only by the mechanical but also by the geometrical properties of the contacting surfaces. Similar effects are well known for non-biological materials [15,26–28,32]. The cuticle tested behaved differently depending on its condition. Fresh cuticle was soft and compliant and had low surface roughness. Desiccation considerably increased its hardness, stiffness and roughness. After chemical treatment, the samples became even harder and stiffer while their roughness was somewhat lower than that of dry ones. There was, however, no considerable difference in hydrophobicity of surfaces: all samples were to the same extent hydrophobic (contact angle of water higher than 90 °). Therefore, an influence of this factor on differences in tribological behavior of the samples studied can be neglected.

In spite of the differences in surface properties, all results showed a strong dependence on the applied load: higher normal loads resulted in higher tangential forces. This effect can be explained by the increase of the contact area with an increasing load (Fig. 8). Correspondingly, the attractive forces between the contacting surfaces were expected to increase [26]. Thus, the tangential force that is necessary to break mechanical interlocking between the contacting surfaces was low at low applied forces and increased with increasing applied load (Fig. 5). According to these considerations, the friction coefficient would be expected to be constant with an increasing applied load. Surprisingly, the opposite dependence was obtained (Fig. 6): The friction coefficient decreased with increasing applied load, most likely because the contribution of adhesion to the normal load becomes negligible at high loads (Eq. (3)).

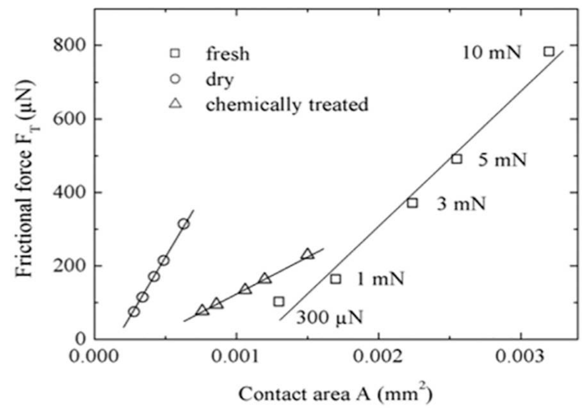

Fig. 10. Friction force versus contact area obtained at different applied loads for fresh, dry and chemically treated *gula* cuticles.

The dependence of the friction force on the contact area is nearly linear in the range of tested loads (Fig. 10). Samples in different conditions showed different relationships between friction behavior and contact area. Dry samples had lower contact area at the same load compared with fresh samples. However, friction of fresh samples was lower at same contact area. This might be attributed to the presence of surface lubrication, which changes after drying of specimens. Chemically treated samples also showed slightly higher friction than fresh samples at same contact area. If we compare dry and chemically treated samples, dry samples had higher friction at same contact area. It is not surprising therefore that the hard, stiff and rough surfaces in the chemically treated state display lower friction coefficients than soft, compliant and smooth fresh cuticles (Fig. 11).

4.4. Contact behavior

The contact area is primarily determined by the mechanical properties of the material. In order to verify a correlation between mechanical properties and contact behavior, the hardness and the elastic modulus were determined by nanoindentation [13]. The contact area increased with increasing applied force for all types of samples. As expected, with hardening and stiffening of the dried cuticle, the contact area considerably decreased. The applied load had a lower influence on the contact area in dried materials. Comparison of dry and chemically treated samples revealed differences in their contact behavior. Both hardness and elastic modulus increased after chemical treatment, but surprisingly so did the contact area (Fig. 12).

To better understand the contact behavior between the fresh *gula* and the glass plate under applied load, the radius of an equivalent contact circle was calculated from experimentally measured contact area and plotted versus applied normal load (Fig. 13). The experimental data are fitted by the Hertz [33] and Johnson-Kendall-Roberts (JKR) [29] contact models. For the fitting, the experimental values of applied load, contact area and the radius of the *gula* (1.3 mm) have been used.

The reduced elastic modulus predicted by the Hertz fit (1.8 GPa) is in excellent agreement with the elastic modulus value measured experimentally by nanoindentation for the fresh *gula* (1.5 ± 0.5 GPa)

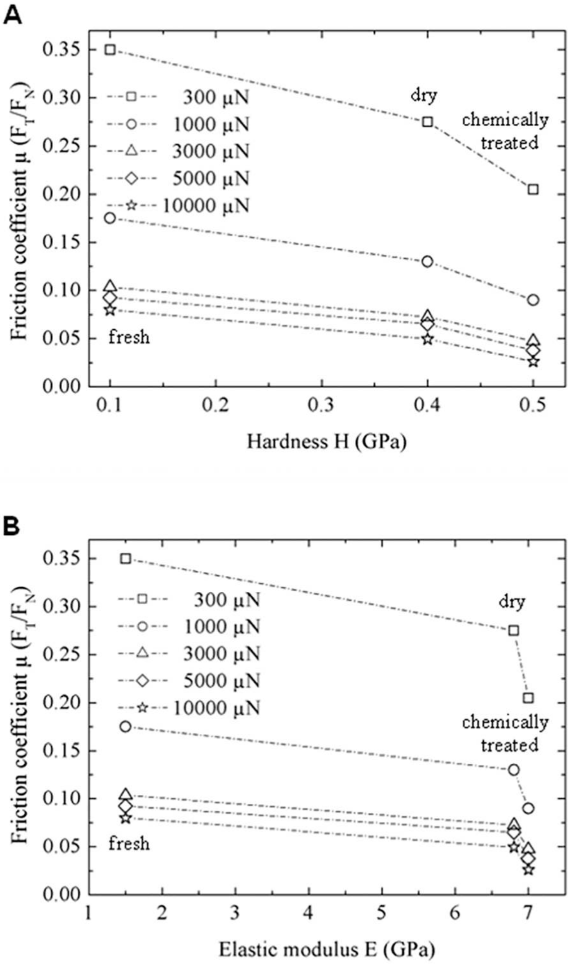

Fig. 11. Dependence of the friction coefficient on hardness (A) and elastic modulus (B) of the *gula*. The hardness and elastic modulus values were determined by nanoindentation [13].

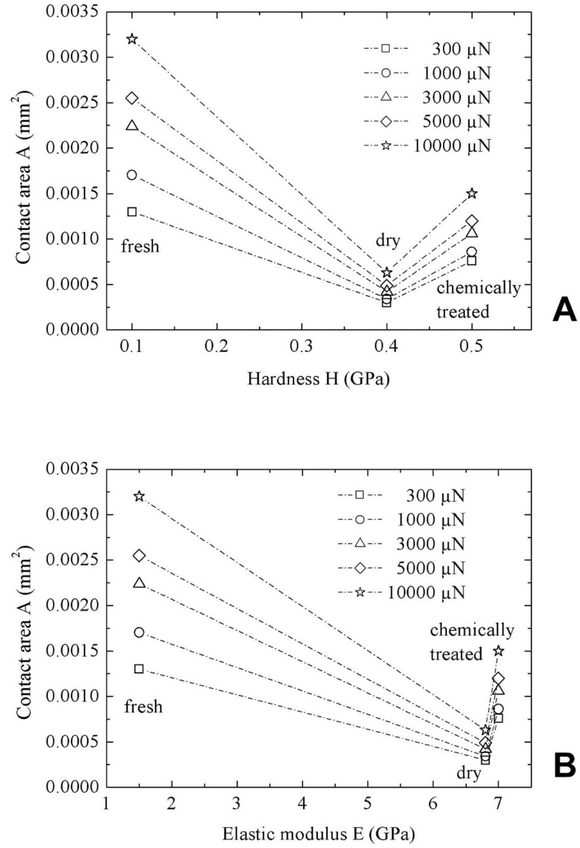

Fig. 12. The contact area versus hardness (A) and elastic modulus (B). The mean values of the hardness and the elastic modulus determined by nanoindentation [13] are shown for fresh, dry and chemically treated cuticles.

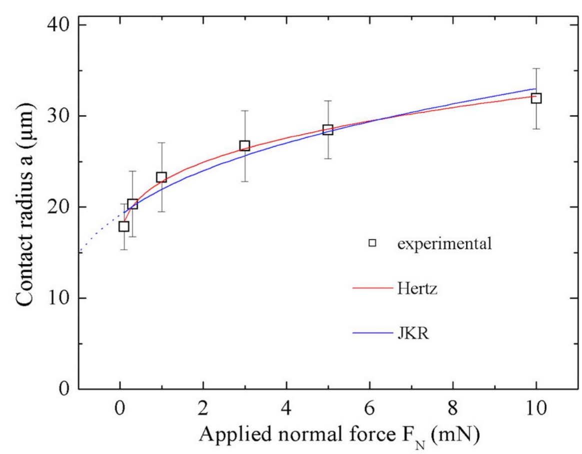

Fig. 13. The contact radius between the fresh *gula* and glass plate determined from the experimentally measured contact area (Fig. 8) versus applied load. The experimental data are fitted by Hertz and JKR contact models. Taking into account that the $a_0 \neq 0$ but $a_0 = 14.68\,\mu m$ by $F_0 = 0$, the Hertz model fits the data better than the JKR model.

[13]. However, the Hertz fit gives the contact radius a_0 corresponding to zero applied force F_0 not 0 as described by Hertz theory, but 14.68 μm. This difference is thought to be caused by several factors. Hertz theory describes contact behavior between two spherical bodies. A non-ideal spherical shape, a microroughness of the *gula* and possible presence of a lubricant in contact area are believed to effect in the non-zero area at zero load. Also the influence of the meniscus forming on the surface asperities due to the intrinsic water layer cannot be completely excluded.

The JKR fit resulted in a reduced elastic modulus of 0.48 GPa which is very low compared to the experimentally measured data (1.5 ± 0.5 GPa). A work of adhesion estimated with the JKR fit was very high (γ = 140 mJ/m2). Correspondingly, the equation

$$F_{pull-off} = -\frac{3}{2}\gamma\,\pi\,R \tag{4}$$

gives a rather high pull-off force value (~0.9 mN), which could not be seen in the experiments.

Based on these estimates, it can be concluded that the contact radius versus applied load can be fitted very well by the Hertz model, and adhesive effects seem to be negligible.

4.5. How can the gula cuticle contribute to friction reduction?

Since the *gula* cuticle is part of a complex biological system that operates in the head-articulation of the living beetle, the properties of the fresh samples in contact with its natural counterpart are important to understand its working principle. However, this kind of micro-tribological test is extremely challenging. That is why friction properties of the *gula* cuticle were studied in contact with the glass plate. We show that the surface of the hemispherical *gula* is very smooth (Fig. 7A) in the fresh condition. Friction between the fresh sample and glass plate can be considered as sliding of two smooth surfaces against one another. Due to the factors mentioned above, this combination exhibits a large contact area and consequently a large shear force. However, in the native condition, the *gula* slides on the *prothorax* surface, which is covered by cuticular outgrowths (Fig. 3B, D). During the relative motion, such two parts in this system will, due to their different structure, not form large area of an intimate contact, but rather a low number of contact points of few micrometers range each. Since the surface of the *gula* cuticle is hydrophobic and the surface of the *prothorax* cuticle is assumed to be hydrophobic as well, the formation of a water film is inhibited. With the decreased contact area and reduced chance for the formation of capillary bridge, friction forces will be reduced. Similar geometrical combinations have been found also in insect leg joints [1,34]. Presumably, such a contact geometry effects in minimization of friction forces as a result of a decrease of the contact area. According to the experiments, this suggestion seems to be correct.

As already shown, friction behavior cannot be determined only by such factors, as the surface roughness and area of contact. Material properties, such as hardness and elastic modulus, are very important and cannot be neglected. Since *prothorax* belongs to the same type of sclerotized cuticle as *gula* and is a part of the same system, it can be supposed that the mechanical properties of the material are nearly the same. However, the cuticular outgrowths of the *prothorax* can considerably change in their mechanical behavior. The microstructure of the *prothorax* counterpart can lead to a decrease of the stiffness (effective elasticity modulus) of the entire structure. In technical ball bearing systems, materials for contacting surfaces should be selected with different hardnesses, such that the shape of the bearing will be determined by the harder surface [35].

The results obtained in this study describe the material properties of the beetle joint adapted for holding and moving the head. It is reasonable to assume that the head articulation system requires low friction for movement of the head, but high friction for the head fixation, for instance, during digging in the soil (behavior which is well known for *Pachnoda marginata*). Low friction can be reached by decreasing the contact area between the smooth and structured surfaces under low load. An increase in contact forces between the *gula* and *prothorax* may increase the contact area due to the deformation of the surface protuberances of the *prothorax* and, consequently, lead to the friction increase.

To understand the entire system of the head articulation of the beetle, further investigations including studies of the *prothorax* counterpart of the *gula*, are necessary. In addition, some suggestions mentioned above can be tested using the contacting pair model of polymers with different shapes and surface microstructure.

5. Conclusions

The tribo-mechanical behavior of the head articulation cuticle of the beetle *Pachnoda marginata* was studied in order to understand the working principle of a materials system presumably evolved for friction minimization. To investigate the effect of desiccation and removal of an outer wax/lipid layer, the samples were tested in three conditions: fresh, dry and chemically treated. The results obtained can be summarized as follows:

(1) The tribo-mechanical behavior of the *gula* cuticle depends on the sample condition. Surface properties are greatly influenced by the moisture content. The removal of the outer wax/lipid layer also changes the mechanical behavior of the samples.
(2) The friction behavior of the *gula* cuticle was found to depend on both the applied load and the contact area. The fundamental laws, describing friction coefficient to be independent of load and contact area at the macroscopic scale, do not seem to hold at the microscopic scale.
(3) The friction at the micrometer range was found to be influenced by various properties of the contacting surfaces. A strong correlation between only one fundamental property and the friction performance could not be found. The friction forces were influenced by the material mechanical properties as well as by the contact area and roughness of the surface.
(4) Two types of correlations between friction and contact area could be detected. Friction decreases with a decreasing contact area after drying. Subsequent chemical treatment increased the contact area, but slightly decreased friction. The friction coefficient decreased with an increasing applied load. All samples revealed a good correlation with the mechanical properties: an increase in hardness and stiffness caused friction to decrease.
(5) The contact behavior of the cuticle tested is found to be fitted well by the Hertz model with a deviation close to zero applied force. The increased experimental value of the contact radius is thought to be caused by non-ideal spherical shape of the *gula* and also possible meniscus formation on the surface asperities.
(6) Fresh *gula* cuticle showed the highest friction coefficient in contact with a glass plate, when compared to the dry and chemically treated samples. In the real system, the *gula* forms contact with the *prothorax* surface covered with anisotropic cuticular outgrowths. A friction reduction in the native system could be expected as a result of the contact area minimization. However, proper description of the working principle of a tribological system is only possible if the material properties of both contacting surfaces are known. Therefore, in the future, investigations on the *prothorax*, the counter-part of the *gula,* are necessary.

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Conflict of interest

None.

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