



## Surface roughness, claw size and leg elasticity influences on the jumping of *Acheta domesticus* crickets

E. Lepore<sup>a</sup>, C. Chappoz<sup>a</sup>, D. Cipriano Monetta<sup>a</sup>, N. Pugno<sup>b,\*</sup>

<sup>a</sup> Laboratory of Bio-inspired Nanomechanics, Giuseppe Maria Pugno, Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

<sup>b</sup> Department of Civil, Environmental and Mechanical Engineering, University of Trento, via Mesiano, 77, I-38123 Trento, Italy

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### ABSTRACT

The jumping of living house crickets (*Acheta domesticus*) on three sandpapers with different roughness and the mechanical properties of their legs have been studied. The longest jumps are observed when the higher friction occurs, that in turn happens when the average particle diameter of each substratum is comparable to the insect's claw diameter. In the longest jump, the cricket *A. domesticus* was propelled forwards for almost 30 cm, about 16 times its body length, to a take-off velocity of 1.8 m/s at an angle of 36.9° with a kinetic energy of 520 μJ, in agreement with previously published studies where the role of friction was not elucidated. In addition, the crickets' legs were also strained at the constant rate of 1 mm/min, using a tensile testing machine. The observed maximum stress, strain and toughness modulus, defined as the area under the stress–strain curve, are 69.4 MPa, 17.4% and 0.72 MJ/m<sup>3</sup>, respectively, and are compatible with the required jumping performances. Finally, we compare the jumping performances of *A. domesticus* with other jumping insects, such as locusts, planthoppers, froghoppers, bush crickets, pygmy mole crickets, false stick insects and stick insects, which were analysed in previously published papers.

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### 1. Introduction

Many animals, insects and spiders have evolved specific mechanisms of defensive actions to displace their bodies rapidly away from imminent predation or unfavourable conditions with a propulsive rapid and coordinated mechanism (e.g. jumps) or as a means of increasing their forward speed of locomotion. In particular, these organisms need to generate a strong mechanical power with a high speed of body response to jump in order to locomote, to capture prey, to escape from unfavourable conditions or to circumvent obstacles [1–4]. This terrestrial locomotor skill requires the coactivation of limbs, skeleton and contractile elements of the muscles which provide additional power required to accelerate or decelerate during locomotion performances [5]. Referring to insects, some of them have evolved long hind legs and use direct muscle contractions to move long levers, while other with short legs have developed catapult mechanisms that store elastic strain energy and then release it suddenly to power the jump [2,5–12]. It is well known that a jumping cycle consists mainly of four sub-phases (propulsion, flight, landing and recovery) and all these

phases must be of short duration with large displacements of the centre of mass to ensure optimal and rapid escape, so long horizontal jumping distance and high takeoff velocity [13]. This mechanism has been exploited by one of the best-known jumping insects such as locusts [2,14–16], which combine energy storage and muscle-bound femurs and can straighten with sufficient force to shove their tibiae against the ground hard enough to propel them upward and forward. Among insects that use their hind legs to propel their jumps, it can be marked the jumping ability of the male locust *Schistocerca gregaria* (body mass of 1.7 g, body length of 50 mm), which are able to jump an average horizontal distance of 875 mm so ~19 times their body length with a takeoff velocity of 3.2 m/s and an energy consumption of 9 mJ [14]; or the adult bush crickets *Pholidoptera griseoaptera* (body mass of 0.4 g, body length of 21.6 mm), which are able to jump an average (maximum) horizontal distance of 302 mm (660 mm) so ~14 (31) times their body length with a takeoff velocity of 1.51 m/s and an energy consumption required for the jump of 0.5 mJ [2]; or the male false stick insect *Prosarthria teretrirostris* (body mass of 0.3 g, body length of 67 mm), which are able to jump an average (maximum) horizontal distance of 660 mm (900 mm) so ~10 (13) times their body length with a takeoff velocity of 2.5 m/s and an energy consumption of 0.85 mJ [8]; or the froghoppers *Philaenus spumarius* (body mass of 0.1 g, mean body length of 6.1 mm), which are able to jump an average (maximum) vertical distance of 428 mm

\* Corresponding author. Address: Department of Civil, Environmental and Mechanical Engineering, University of Trento, via Mesiano, 77, I-38123 Trento, Italy.  
E-mail address: [nicola.pugno@unitn.it](mailto:nicola.pugno@unitn.it) (N. Pugno).

(700 mm) so  $\sim 70$  (115) times their body length with a takeoff velocity of 2.8 m/s and a maximum energy consumption of 0.5 mJ [7]; or the coleorrhynchan *Hackeriella veitchi* (body mass of  $1.3 \times 10^{-3}$  g, body length of 1.9 mm), which are able to jump an average horizontal distance of 150 mm so  $\sim 77$  times their body length with a takeoff velocity of 1.2 m/s and an energy consumption of  $0.85 \times 10^{-3}$  mJ [5].

As a matter of fact, insects' attachment systems are evolving also as adaptation for efficient locomotion on different substrata. In particular, insects developed a variety of leg adaptations in order to facilitate attachment on a multitude of natural substrata, which in turn could change the insect-plant interaction only by the mediation of surface roughness [17,18]. In order to produce propulsive forces, the insect locomotory systems must be capable to engender a satisfactory friction with a specific substratum, so their mechanism of claw action plays an important role as an add-on capacity [19].

Many scientists have studied a large number of insects in order to understand their jumping systems and how the attachment force is related to the claw dimension and the surface roughness. In general, claw-mediated adhesive insects (including stick insects [20], chrysomelidae [17], beetles [18,21,22], grasshoppers [14], fleas [23,24] and flea beetles [25–28]) have been studied as a good source for biorobotics by many researchers, since they can attach to horizontal or vertical surfaces only by claw interlocking. The adhesive, and so jumping, abilities find an optimum at a certain grade of surface roughness [29–32], in agreement with our observations. In particular, the claw-mediated adhesion occurs when the surface asperity size is comparable or larger than the cricket's claw diameter [18,33,34], here estimated to be  $\sim 335 \mu\text{m}$ . It is clear that insect claws become in contact with the surface during the insect locomotion with a certain grade of interaction; if the friction is adequate to avoid sliding, claws turn into driving mechanism to generate propulsive forces [35].

In this paper, we describe the jumping trajectory of living house crickets (*Acheta domesticus*) on three sandpapers with different roughness and compare the jumping performances with the most accomplished jumping insects, such as locusts, planthoppers, frog-hoppers, bush crickets, pygmy mole crickets, false stick insects and stick insects, which were analysed in previously published papers. The micro-structured roughness of different substrata has been previously determined by means of microscopic analysis instruments (Field Emission Scanning Electron Microscope (FESEM) and Atomic Force Microscope (AFM)). The adhesive system of crickets was just analysed by FESEM. We demonstrate a clear correlation between the diameter of the cricket's claw diameter and the surface roughness. When the average particle diameter of each substratum is comparable to the insect claw diameter, the cricket generates the most efficient degree of interaction with the surface irregularities, resulting in the longest parabolic jumping trajectory. On the contrary, when the relative size of the surface roughness is smaller or bigger than the insect claw diameter, the contact frictional interactions between the claw and the surface particles decrease, showing a horizontal jumping distance shorter than that observed in the most efficient condition. In addition, we conduct tensile tests on the legs of crickets, finding as an upper bound the longest jump which is compatible with their elasticity and strength.

## 2. Materials and methods

Male or female house crickets (*A. domesticus* Linnaeus) from a laboratory stock were kept in cages ( $56 \times 39 \times 28 \text{ cm}^3$ ) with cardboard refuges. Food (chicken feed) and water were available *ad libitum* throughout this study. At the conclusion of these experiments, all crickets were returned to the breeding colonies.

### 2.1. Experimental jumping set-up

A self-built jumping arena was used to measure the crickets trajectories during jumps. This procedure allowed us to avoid any prior treatment of the crickets, which are left free of motion and of assuming a natural jumping position inside the experimental arena.

The experimental arena is composed of three vertical panels of Poly(methyl methacrylate) (PMMA) (named A, B and C in Fig. 1) and a small opening (O) replaces the fourth vertical side of the platform, as shown in Fig. 1. The small opening stimulates the cricket to jump in that direction and to fall inside the small cylindrical box (TD), so we standardized the cricket's position of touchdown. The central part of the arena bottom is covered with tested substrata (S), which are of three types of sandpapers (Sp50, Sp80 and Sp150) 215 mm long and from 65 mm to 130 mm wide. All substrata are tested one-by-one. The cricket jumping performance was measured by placing animals approximately in the central area of sandpapers, which represent the cricket's takeoff position (TO). Crickets' jumps were encouraged by delicately tapping a stick once the cricket reaches the TO position. Thus, we standardized the cricket's position of both the takeoff and touchdown for each jump.

A cricket could jump in any direction relative to the camera, but the constraints of the arena ensured that jumps were in the image plane of the video camera, or as close as possible to this plane (black dotted line in Fig. 1). All analyses of the kinematics are based on the two-dimensional images provided by a single camera. This experimental approach is coherent with recently published papers [9,11]. Sequential images of 10 jumps from each of the 3 substrata by 3 adults of either sex were captured with a DCR SR55E SONY digital video camera. Thus, in the movie (in Fig. 1, the blue lines identifies the video shot) it is possible to see both the cricket's takeoff and touchdown, and the cricket trajectory was reconstructed by points. Each video was imported into ImageJ 1.41o software to extract four snapshots (time-interval of 0.04 s) of the cricket's jumping period. Then, the alignment of the images and the numerical reconstruction of the jumping coordinates were obtained using ADOBE® PHOTOSHOP® CS4 (di Adobe Systems Incorporated). Finally, data were imported into Excel (Microsoft) to recalculate the jumping trajectories, so the maximum horizontal jumping distances, the takeoff angle, the takeoff velocity and the energy expenditure were subsequently determined.

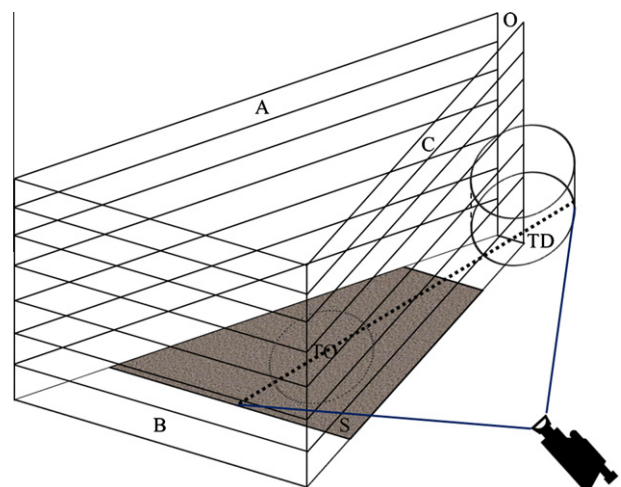


Fig. 1. Experimental arena to perform the cricket's jumping measurements.

Experiments were conducted upon three adult crickets of the species *A. domesticus*. The crickets were maintained at  $\sim 25^\circ\text{C}$  and  $\sim 50\%$  of humidity, which corresponds also to the experimental conditions. We measured the average body length of the three crickets (equal to  $19.1 \pm 2.6$  mm) and the average body mass (equal to  $340.0 \pm 135$  mg), using a Orma EB200 balance with a precision of  $\pm 0.1$  mg.

Since the air resistance of the cricket during jumping and aerodynamic effects were neglected, the takeoff velocity ( $V_0$ ) and the maximum horizontal jumping distance ( $x_{\max}$ ) were calculated using the following equations:

$$V_0 = \sqrt{\frac{g}{2h_{\max}}(x_{\max}^2 + 4h_{\max}^2)} \quad (1)$$

$$x_{\max} = \frac{V_0^2 \sin(2\theta)}{g} \quad (2)$$

where  $g$  is the acceleration of gravity,  $h_{\max}$  and  $x_{\max}$  is the maximum height of the jump and its corresponding horizontal distance and  $\theta$  is the takeoff angle. Thus, the jumping energy ( $E_j$ ) stored in the legs and then released as kinetic energy, which depends on the body mass ( $M$ ) and the takeoff velocity ( $V_0$ ), is:

$$E_j = MV_0^2/2 \quad (3)$$

and thus [14]:

$$E_j = \frac{Mgx}{2 \sin(2\theta)} \quad (4)$$

where  $x$  is experimentally determined.

## 2.2. FESEM characterization

We observed the adhesive system (Fig. 2) and the fracture surfaces of the tensile-tested leg (Fig. 3) of *A. domesticus* by means of a FESEM (FEI-Inspect™ F50 at 1 kV) and a SEM/FIB (FEI Quanta 3D FEG at 20 kV) and the three sandpapers (Fig. 4) just by means of the SEM/FIB (FEI Quanta 3D FEG at 20 kV) equipped with a field emission tungsten cathode. Biological samples were amputated from naturally dead adult crickets, maintained in 70% ethanol solution and 12-h dehydrated before analysis, while sandpapers are used as were. Samples were fixed to aluminium stubs by double-sided adhesive carbon conductive tape (Nisshin EM Co. Ltd.) and scanned without metallization.

Fig. 2 confirms by images the adhesive system description recently reported in [18], showing a sub-obsolete nonfunctional arolium (no better adapted for climbing a smooth vertical surface)

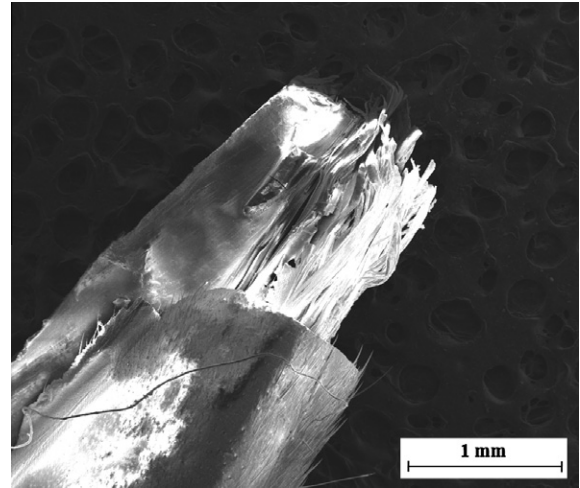


Fig. 3. The fracture surface of a tensile-tested leg of *Acheta domesticus*.

with two claws for each of the six legs of *A. domesticus*. The mean diameter of the cricket's claw is equal to  $335.1 \pm 28.09$   $\mu\text{m}$ . Fig. 3 reports the fractured surface of a tensile-tested leg of *A. domesticus*.

In order to statistically characterize sandpapers, we have approximated the particle shape to a circular shape and so the diameter of each circular particle was determined using the software ImageJ 1.41o. We considered 10 measurements of the particle diameters for each sandpaper, so the average particle diameters of the three sandpapers were calculated to be equal to  $541.1 \pm 39.17$   $\mu\text{m}$  (Sp50),  $346.6 \pm 65.61$   $\mu\text{m}$  (Sp80) and  $135.8 \pm 28.13$   $\mu\text{m}$  (Sp150).

## 2.3. Tensile testing

We collected 20 crickets of different weight and length. We isolated the femur parts of both the right and the left leg and they were kept for a month at a temperature of  $\sim 25^\circ\text{C}$ . Then, we glued (with Attack®) the dry femurs to  $30 \times 40$  mm<sup>2</sup> cardboard holders, which had a  $\sim 3 \times 20$  mm<sup>2</sup> hole in their center so that the samples could be mounted on the testing machine without being damaged. All tests were performed with an air temperature of  $\sim 25^\circ\text{C}$  and  $\sim 30\%$  of relative humidity.

Tensile tests were conducted on twenty specimens using a testing machine (Insight 1 kN, MTS, Minnesota, USA), equipped with a

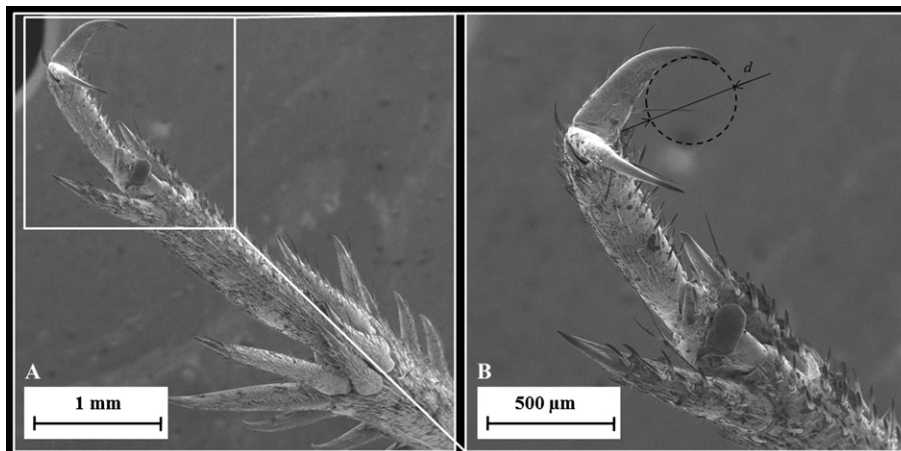


Fig. 2. Adhesive structures on the legs of *Acheta domesticus*. (A) Lateral view of a leg and the claws of each leg (B) ( $d$  is the claw diameter).



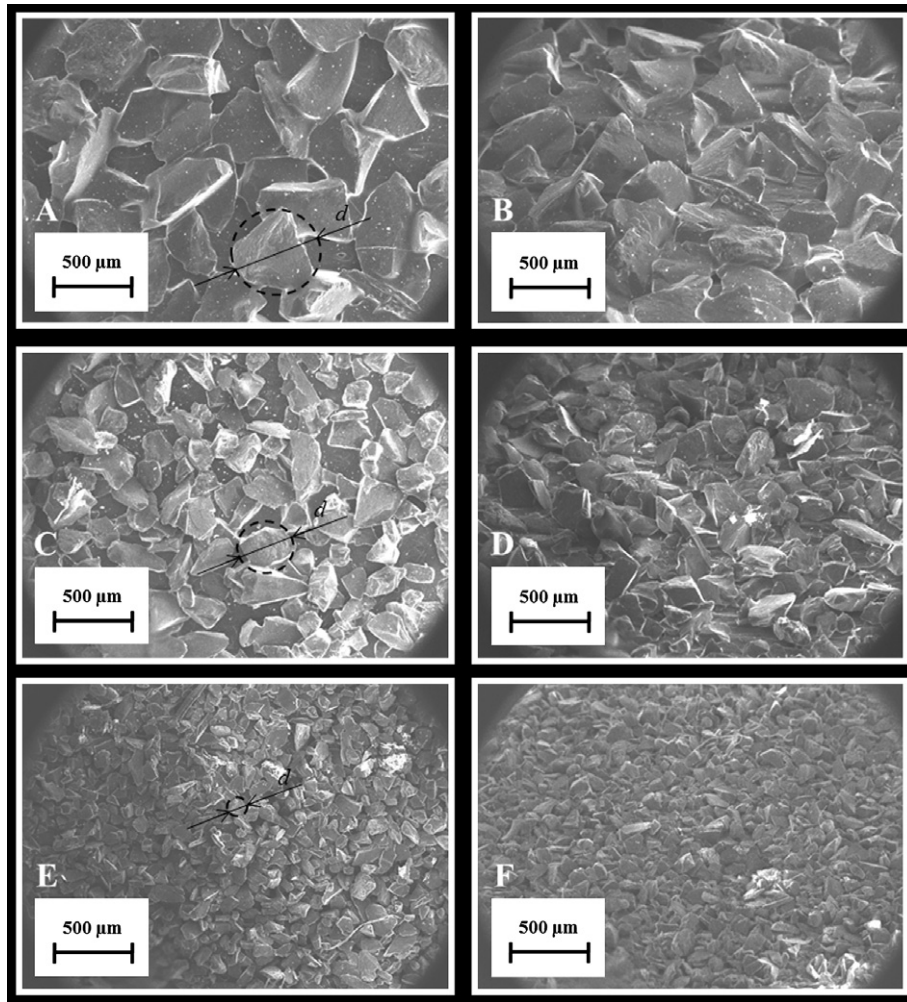


Fig. 4. The surface morphology of the three sandpapers, which were the experimental substrata at 0° (left) and 52° (right) of inclination of the sample stage: the sandpaper Sp50 (A and B), the sandpaper Sp80 (C and D) and the sandpaper Sp150 (E and F) ( $d$  is the particle diameter).

10 N cell load with pneumatic clamps. The cardboard holders were placed between the clamps defining an initial length  $l_0$  of 3 mm. Once the holders were in place, the clamps were brought to zero tension and then the sides of the holders were cut, leaving the samples loose between the clamps. The specimens were pulled until they completely broke at a constant rate of 1 mm/min.

The computer program TestWorks 4 (MTS, Minnesota, USA) recorded the experimental data of the applied tensile force and then the stress-strain curves were computed using the estimation of the real diameter at the femur cross-section. Stress  $\sigma$ , strain  $\varepsilon$  and Young's modulus  $E$ , were calculated using the following equations:

$$\sigma = \frac{F}{A_c} \quad (5)$$

$$\varepsilon = \frac{\Delta l}{l_0} \quad (6)$$

$$E = \left. \frac{d\sigma}{d\varepsilon} \right|_0 \quad (7)$$

where  $F$  is the force measured by the testing machine,  $A_c$  is the initial cross-sectional area of the femur,  $l_0$  is the initial length of the femur and  $\Delta l$  is the change in femur length during test. The area under the stress-strain curve gives the energy required to break the material and this variable can be used to quantify toughness.

### 3. Results

Fig. 5 reports the jumping trajectories for each substratum, while Table 1 shows the calculated jumping performances on the three tested surfaces.

The best jumping performances ( $23.7 \pm 4.58$  cm so 13.4 times the cricket's length) is achieved on intermediate-roughness Sp80 substratum, while crickets show a similar horizontal jumping distance on the least (Sp150) and the last (Sp50) rough surfaces ( $18.1 \pm 5.15$  cm so 10.3 times the cricket's length, and  $17.8 \pm 2.50$  cm so 10.1 times the cricket's length, respectively). The highest cricket's takeoff velocity and angle are on Sp80 ( $1.4 \pm 0.26$  m/s and  $49.5 \pm 8.31^\circ$ ) and Sp50 ( $1.4 \pm 0.16$  m/s and  $50.3 \pm 11.46^\circ$ ), whereas the lowest velocity is on Sp150 ( $1.3 \pm 0.20$  m/s and  $47.8 \pm 11.14^\circ$ ). Finally, the highest jumping kinetic energy is of  $417 \pm 82.32$   $\mu$ J on Sp80, the lowest value on Sp150 ( $322 \pm 76.06$   $\mu$ J) and the intermediate value is on Sp50 ( $330 \pm 65.91$   $\mu$ J).

From the various tensile tests on the legs, we calculated the average failure stress, which was 6.764 MPa even if very scattered. The average failure strain was 16.4%, while the ultimate strain is of  $0.17 \pm 0.06$  mm/mm, which is comparable with the results for the elytra of dung beetle  $0.24 \pm 0.10$  mm/mm [36]. The average value of toughness was  $0.72$  MJ/m<sup>3</sup>. Young's modulus is calculated as the slope of the linear section of the stress-strain curve and is close

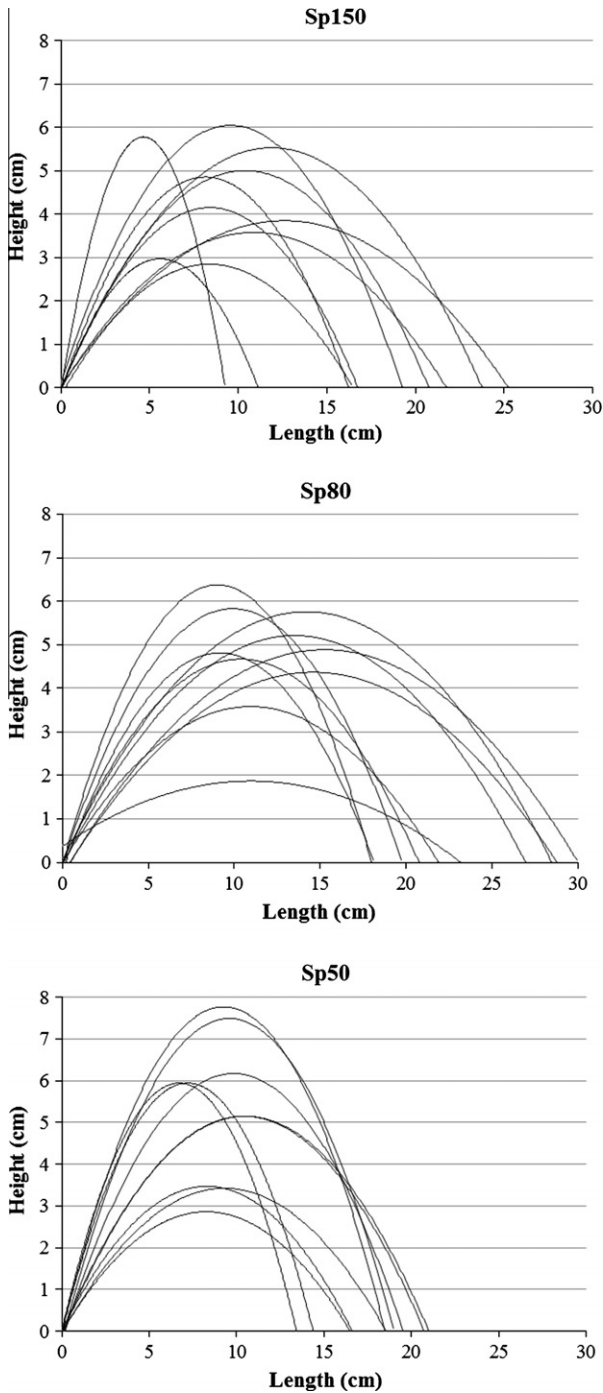


Fig. 5. The jumping trajectories for each substratum.

to 69.3 GPa. Fig. 6 shows the various stress–strain curves that were characterized.

4. Discussion

The influence of the substratum roughness on frictional properties of an animal claw, and so on the animal jumping abilities has been deeply studied [18,30,33,34,37–42]. Referring to claw-mediated adhesive insects, it is well-known that the claw-mediated adhesion arises only when the surface asperity size is comparable with the claw diameter [18,33,34]. In our case, the cricket’s claw diameter is estimated to be ~335 μm, while the average particle diameters of the three sandpapers were of ~541 μm (Sp50), ~347 μm (Sp80) and ~136 μm (Sp150). Coherently with expectations, crickets produce a substantially better jumping performance on the intermediate-rough substratum (Sp80), where it clearly happens that the average sizes of both surface particles and cricket’s claw are similar (see Table 1). An expected result concerns the roughest substratum (Sp50): on such a substrate crickets show jumping performances similar to the least rough substratum (Sp150). A plausible explanation is that, since surface particles of Sp50 (Sp150) surface are almost twice as large (small) than the claw diameter, they are too large (small) to provide the claws with a sufficient grip. Therefore, on Sp50 and on Sp150, the claw–particle interaction is not optimal and determines the worst performances, if compared to the intermediate Sp80 substratum.

Referring to the cricket’s best jumping performance on Sp80, it is interesting to consider a comparison (Table 2) with the most accomplished jumping insects, such as locusts, planthoppers, frog-hoppers, bush crickets, pygmy mole crickets, false stick insects and stick insects. Crickets (weight of ~0.34 g and 1.9 cm long) of species *A. domesticus* can be propelled forwards for 23.7 cm or 12 times its body length. By comparison, other heavier orthopterans such as a locust, which have a weight one order of magnitude higher than crickets, can jump a forward distance up to ~24 times its body length, while a male false stick insect (its weight is of the same order of magnitude of crickets *Acheta*) reaches a distance of ~10 times its body length. Most notable among the other groups within the Orthoptera with species that are reported to jump are pygmy mole crickets, which weight two order of magnitude less than other house crickets, and can jump 85 times their body length. The lighter Hemipteran insects all fell well long of the performances of Orthopteran insects; in particular the planthopper *Issus coleoptratus* reaches distances up to 164 times its body length. Finally, wingless and winged stick insects perform jumps of few body length.

Our data of jumping performances of *A. domesticus* are coherent with previously published results [43], which reported a range of horizontal jumping distances from 8 to 50 cm and of the take-off velocity from 1 to 3 m/s<sup>2</sup>.

Table 1

The calculated jumping performance for each surface: the horizontal jumping distance, its value divided by the cricket length, the takeoff velocity, the takeoff angle and the jumping kinetic energy.

	Sp150	Sp80	Sp50
Experimental horizontal jumping distance (cm)	18.11 ± 5.15	23.70 ± 4.58	17.84 ± 2.50
Theoretical horizontal jumping distance (cm)	17.78 ± 5.96	20.90 ± 7.50	18.60 ± 3.84
Jumping distance divided by cricket length	10.3 ± 2.91	13.4 ± 2.59	10.1 ± 1.42
Initial velocity (m/s)	1.3 ± 0.20	1.4 ± 0.26	1.4 ± 0.16
Take-off angle (°)	47.8 ± 11.14	49.5 ± 8.31	50.3 ± 11.46
Energy (μJ)	322 ± 76.06	417 ± 82.32	330 ± 65.91

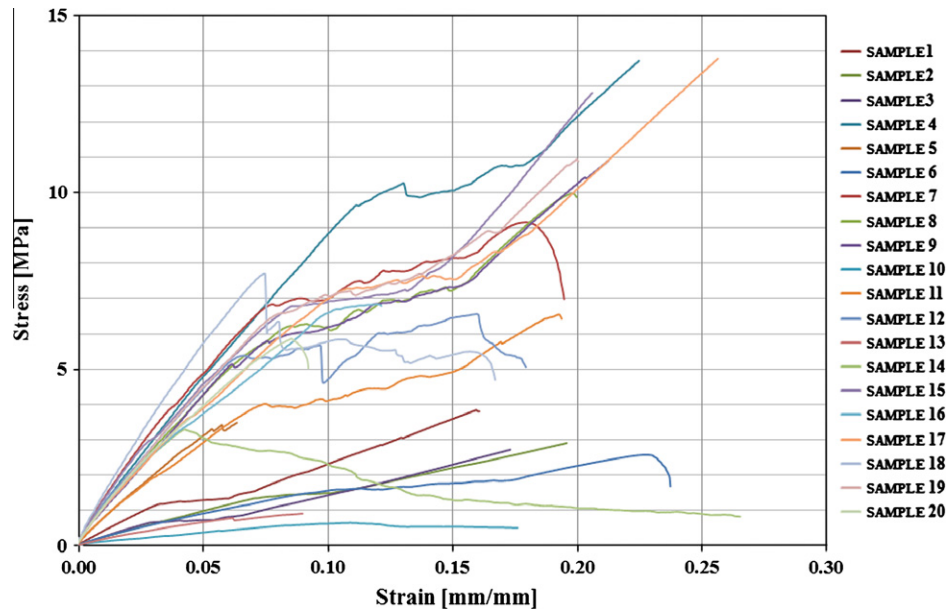


Fig. 6. Stress–strain curves of cricket's femurs.

**Table 2**  
Comparison of the jumping performance of *Acheta domesticus* (data from this paper) with some other jumping insects (data from the literature). Measurements are given as means ( $\pm$ standard deviation).

References	Order	Family	Species	Mass (mg)	Body length (mm)	Experimental horizontal jumping distance (cm)	Jumping distance/body length	Initial velocity (m/s)	Take-off angle ( $^{\circ}$ )	Energy ( $\mu$ J)
[7]	Hemiptera	Aphrophoridae	<i>Neophilaenus exclamationis</i>	$3.2 \pm 0.08$	$4.0 \pm 0.03$	Not given	Not estimated	$4.2^a$	55	$28^a$
[7]	Hemiptera	Aphrophoridae	<i>Philaenus spumarius</i>	$12.3 \pm 0.74$	$6.1 \pm 0.08$	$42.8 \pm 2.6$	70	$2.8 \pm 0.1$	$46.8 \pm 2.0$	48
[7]	Hemiptera	Cercopidae	<i>Lepyronia coleoptrata</i>	$17.6 \pm 0.18$	$7.2 \pm 0.18$	Not given	Not estimated	4	90	141
[7]	Hemiptera	Aphrophoridae	<i>Aphrophora alni</i>	$28.3 \pm 1.1$	$9.8 \pm 0.24$	$26.3 \pm 2.0$	27	2.5	Not given	88
[7]	Hemiptera	Cercopidae	<i>Cercopis vulnerata</i>	$32.9 \pm 1.0$	$9.5 \pm 0.13$	Not given	Not estimated	$3.8^a$	45	$258^a$
[12]	Hemiptera	Issidae	Male <i>Issus coleoptratus</i>	$21.5 \pm 0.56$	$6.7 \pm 0.07$	$110^a$	$164^a$	$3.2 \pm 0.21$	$42.7 \pm 1.8$	$121 \pm 14.9$
This study	Orthoptera	Gryllidae	<i>Acheta domesticus</i>	$340.0 \pm 135$	$19.1 \pm 2.6$	$23.70 \pm 4.58$	12	$1.4 \pm 0.26$	$49.5 \pm 8.31$	$417 \pm 82.32$
[43]	Orthoptera	Gryllidae	<i>Acheta domesticus</i>	$\sim 500$	Not given	$8-50^b$	Not estimated	$1-3^b$	$15-45^b$	Not given
[2]	Orthoptera	Tettigoniidae	Male <i>Pholidoptera griseoaptera</i>	$415 \pm 20$	$21.6 \pm 0.6$	$30.2 \pm 1.15$	14	$1.51 \pm 0.2$	$33.8 \pm 2.1$	490
[9]	Orthoptera	Tridactylidae	<i>Xya capensis</i>	$8.3 \pm 0.07$	$5.6 \pm 0.12$	$47.7 \pm 2.7$	85	$5.0 \pm 0.12$	$85 \pm 3.53$	$116 \pm 15.1$
[2]	Orthoptera	Acrididae	Male <i>Schistocerca gregaria</i>	$1600 \pm 35$	$41.4 \pm 1.2$	100	24	3.2	45	$(9-11) \times 10^{3b}$
[14]	Orthoptera	Acrididae	Male <i>Schistocerca gregaria</i>	$(1.5-2) \times 10^{3b}$	50	$80-95^b$	18	3.2	Not given	$9 \times 10^3$
[15]	Orthoptera	Acrididae	<i>Schistocerca gregaria</i>	$1600 \pm 460$	Not given	$70 \pm 19$	Not estimated	$2.62 \pm 0.35$	Not given	Not given
[16]	Orthoptera	Acrididae	<i>Oedaleus infernalis</i>	Not given	Not given	$49.3 \pm 0.04$	Not estimated	$2.4 \pm 0.3$	$42.5 \pm 0.1$	Not given
[8]	Orthoptera	Proscopiidae	Male <i>Prosarthria teretirostris</i>	$280 \pm 10$	$67.5 \pm 0.8$	$66 \pm 6.7$	10	$2.5^a$	40.7	$850^a$
[10]	Phasmatodea	Timematidae	Female <i>Timema chumash</i>	$47.5 \pm 7.3$	$12.0 \pm 0.68$	$8^a$	$7^a$	$0.53 \pm 0.02$	$38.9 \pm 2.46$	7
[11]	Phasmida	Heteronemiidae	Male <i>Sipyloidea</i> sp.	$164 \pm 4.6$	$65 \pm 0.5$	Not given	Few body lengths	$0.6 \pm 0.03$	$10-35^b$	96

<sup>a</sup> Value of the best jump.

<sup>b</sup> Range of measured values.

Referring to the tensile results of the mechanical characterization of femurs, we could find out another confirmation of the experiments, considering the following equation:

$$E_j = 2 \times E_f \quad (8)$$

where  $E_j$  is the jumping energy given by Eq. (3), the multiplier 2 is to consider the two legs of a cricket and  $E_f$  is the elastic energy of a cricket's leg and is equal to:

$$E_f = \frac{EA}{2l} \Delta l^2 = \frac{EV\varepsilon^2}{2} = \frac{EfM\varepsilon^2}{2\rho} \quad (9)$$

where  $E$  is the measured elastic modulus of femurs,  $f$  is the fraction of the cricket's femur mass compared to the total mass  $M$ ,  $\varepsilon$  is the measured ultimate strain of femurs and  $\rho$  is the cricket's femur density.

From Eqs. (3) and (9), we obtain the takeoff velocity as:

$$v_0 = \sqrt{\frac{fE\varepsilon^2}{\rho}} \quad (10)$$

while the maximum horizontal jumping distance is derived from Eqs. (4) and (8) as:

$$x_{\max} = \frac{fE\varepsilon^2}{\rho} \frac{\sin(2\theta)}{g} \quad (11)$$

For  $E$  and  $\varepsilon$ , we consider the minimum values which were obtained during our tensile tests of 7 MPa and 0.04 mm/mm, respectively. The fraction  $f$  of the cricket's femur mass is considered equal to 0.1,  $\theta$  is the mean value of the takeoff angles,  $g$  is the gravity acceleration and  $\rho$  is 1200 kg/m<sup>3</sup>, as assumed and reported in a previously published paper [14].

Thus, the takeoff velocity and the maximum horizontal jumping distance were also obtained from the experimental data of the mechanical characterization of cricket's femurs and they were equal to 1.4 m/s and 18.8 cm, respectively. These results are clearly coherent with the experimentally measured mean takeoff velocities and maximum horizontal jumping distances, which are summarized in Table 1, suggesting that the stored elastic energy in the legs is closed to the maximal value before jumping and thus the biological system is optimized also in the context.

## 5. Conclusions

In this paper, the jumping performances of living house crickets (*A. domesticus*) on three sandpapers were determined. We have demonstrated a clear correlation between the diameter of the cricket's claw and the surface roughness. Crickets generate the best jumps when the most efficient interaction with the surface irregularities occurs, so when the average particle size of each substratum is comparable to the insect claw diameter. Also, we found out an interesting correlation between the experimental result of crickets' jumping performances and those obtained taking into account the mechanical data of tensile tests, which allow us to confirm the experimental jumping results and demonstrate that the biological system is mechanically optimized. Finally, we compare the jumping performances of *A. domesticus* with those published by other authors, and also for other insects, finding a good agreement.

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