Adhesive force of a single gecko foot-hair

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Geckos are exceptional in their ability to climb rapidly up smooth vertical surfaces[1-3]. Microscopy has shown that a gecko's foot possesses nearly five hundred thousand keratinous hairs or setae. Each 30 – 130 µm long seta is only one-tenth the diameter of a human hair and contains hundreds to thousands of projections terminating in 0.2 - 0.5 µm spatula-shaped structures[2, 4]. After nearly a century of anatomical description[2, 4-6], we report the first direct measurements of single setal force by using a two-dimensional micro electro mechanical systems (MEMS) force sensor[7] and a wire as a force gauge. Surprisingly, measurements revealed that a seta is ten times more effective at adhesion than predicted from maximal estimates on whole animals. Adhesive force values support the hypothesis that individual seta operate by van der Waals forces[8, 9]. The gecko's peculiar behavior of toe uncurling and peeling led us to discover two novel aspects of setal function which increase their effectiveness. A unique macroscopic orientation and preloading of the seta increased attachment force 600-fold above that of frictional measurements of the material. Suitably orientated seta reduced the forces necessary to peel the toe by simply detaching above a critical angle with the substratum.

The foot of a Tokay gecko (*Gekko gecko*) holds approximately 5000 setae mm^{-2} [4] and can produce 10 N of adhesive force with approximately 100 mm^2 of pad area[10] (Fig. 1a-d). Therefore, one predicts that each seta should produce an average force of 20 μN and an average stress of 0.1 N mm^{-2} (~1 atm). The actual magnitudes could be greater, since it is unlikely that all setae adhere simultaneously. We measured force production by single, isolated seta during attachment using a novel micromachined, dual-axis, piezoresistive cantilever (Fig. 1e).

To determine the protocol of how setal force should be measured, we considered the gecko's unusually complex behavior of toe uncurling during attachment, much like an inflatable party favor, and toe peeling during detachment, analogous to how we remove a piece of tape from a surface. The exquisite control of the toe allowed us to discover novel aspects of the setal function by suggesting that orientation and loading could be crucial to its capacity. Setal force did, in fact, depend on three-dimensional orientation (spatulae pointing toward or away from the surface) and the extent to which the foot-hair was preloaded (pushed into and pulled along the surface) during the initial contact. Contacting the surface with the seta in a direction other than with spatulae projecting toward the surface resulted in forces less than 0.3 μN when the seta was pulled away perpendicular to the surface. By contrast, when the active spatular region was projecting toward the surface, force increased enormously. After an initial push toward the surface, which we term a perpendicular preload, the seta was pulled parallel to the surface. Setal adhesive force parallel to the surface increased consistently until the seta began to slide off the edge of the sensor (at time t_s, Fig. 2a). Setal force parallel to the surface increased linearly with the perpendicular preloading force and was substantially greater than the force produced by the inactive, non-spatular region at all preloads (Fig. 2b). Experiments in which setae were pulled away from the surface of a wire (Fig. 1f) demonstrated that perpendicular preloading alone is insufficient for effective setal attachment. Setae that were first pushed into the surface and then pulled parallel to it developed over ten times the force (13.6 μN ± 2.6 SD; N = 17) upon being pulled away from the surface than those having only a perpendicular preload (0.6 μN ± 0.7 SD; N = 17). The largest parallel forces were observed only if the seta was allowed to slide approximately 5 μm along the sensor's surface, a distance imperceptible at the level of the foot (Fig. 3). The maximum adhesive force of single seta averaged 194 μN ± 25 SD (N = 28), nearly 10-fold greater than predicted from maximal whole animal estimates. Our single-seta force measurements suggest that if all setae were simultaneously and maximally attached, a single foot of a gecko could produce 100 N of adhesive force (~10 atm). The results of preloading on setal force production support the hypothesis that a small perpendicular preloading force in concert with a rearward displacement or parallel preload may be necessary to "engage" adhesion[4]. Since the tips of the setae are directed rearwards away from the toenail, preloading may increase the number of spatulae contacting the surface[11].

The orientation of the setae was also important in detachment. The force produced when a seta was pulled away from the surface was not significantly different from the force measured during a pull parallel to the surface if the same perpendicular preload was given. However, we found that setae detached at a similar angle (30.6° ± 1.8 SD; N = 17) when pulled away from the wire sensor's surface. To check for the presence of a critical angle of detachment, we controlled perpendicular force and progressively increased the setal angle (α; Fig. 1f) until detachment. Setal angle at detachment changed by only 15% over a range of perpendicular forces (Fig. 4). This observation is consistent with an adhesive model where sliding stops when pulling at greater than the critical setal angle and hence stress can increase at a boundary, causing fracture of the contact. Change in the orientation of the setae and perhaps even the geometry of the spatulae may facilitate detachment. It has long been known that geckos peel the tips of their toes away from a smooth surface during running[2]. Toe peeling may have two effects. First, as we discovered here, it may put an individual seta in an orientation or at a critical angle that aids in its release. Second, toe peeling concentrates the detachment force on only a small subset of all attached setae at any instant.

Our direct setal force measurements reject two of the proposed mechanisms of adhesion, suction[12, 13] and friction[6, 14], and provide indirect support for the most favored hypothesis, intermolecular forces[8, 9]. Our measurements of greater than one atmosphere of adhesion pressure strongly suggest that suction is not involved and lends support to previous measurements carried out in a vacuum[5]. The present data do not support a friction mechanism[6, 14], because the cantilever's surface was smooth (surface roughness less than or equal to 2.5 nm) and the coefficient of friction of the setal keratin on silicon was low ($\mu = 0.25$; Fig. 2b; dashed line). Microinterlocking[14] could function as a secondary mechanism, but the ability of geckos to adhere to polished glass shows that irregularities on the scale of the spatulae are not necessary for adhesion[1]. Previous experiments using X-ray bombardment[5] have eliminated electrostatic attraction[15] as a mechanism necessary for setal adhesion, since the setae can still adhere in ionized air. Adhesion by glue is an unlikely mechanism, since skin glands are not present on the feet of lizards[5, 14, 16]. However, the role of adsorbed water requires further study[11].

Our direct setal force measurements are consistent with the hypothesis that adhesion in geckos is the result of intermolecular forces[8, 9]. Earlier experimental support for the van der Waals hypothesis[4, 9] comes from the observation that adhesive force of a whole gecko increases with increasing surface energy of the substrate[8, 9]. The simple models available can only give the most approximate estimates of setal force production. If we assume that the tip of a spatula is a curved segment of a sphere (radius, $R = 2\mu m$) and is separated by a small distance from a large, flat surface where van der Waals forces become significant (atomic gap distance, $D \approx 0.3$ nm), then setal force = $AR / 6D^2$ where A is the material dependent Hamaker constant taken to be 10^{-19} J[17]. This estimate puts the van der Waals force for a spatula to be about 0.4 μN. Since the number of spatulae per seta varies from 100 to 1000, setal force estimates range from 40 to 400 μN, a range within which our direct measurements fall. The uncertainty in this estimate points to the need for future data collection on spatular morphology, orientation, spacing and material properties. Van der Waals forces are extremely weak at greater than atomic distance gaps, and require intimate contact between the adhesive and the surface. Polymeric adhesives such as tape are soft, and are able to deform sufficiently for intimate contact over a relatively large surface area[18, 19]. The feet of a Tokay gecko (*Gekko gecko*) contain approximately one billion spatulae that appear to provide a sufficiently large surface area in close contact with the substrate[4] for adhesion to be the result of van der Waals forces. Although manufacturing small, closely packed arrays mimicking setae are beyond the present-day limits of human technology, the natural technology of gecko foot-hairs can provide biological inspiration for future design of a remarkably effective dry adhesive.

Methods.

Preparation of single seta. We carefully peeled the cuticular layer of a single row of lamellae off the toe of a restrained, live, non-moulting gecko. With a finely etched tungsten pin, we scraped the cuticular surface to break off individual setae at the base of the stalk. The isolated seta was then glued to the end of a #2 insect pin with 5-minute® epoxy (TTWDevcon, Danvars, MA). The pin had a tip diameter of approximately 15 µm. To prevent the epoxy from creeping up the stalk of the seta, which might change the mechanical property of the specimen, we pre-cured the epoxy for approximately 1 min before applying it to the specimen. All setae were oriented such that the active surface was approximately perpendicular to the axis of the pin. All preparations were completed under a compound microscope.

Force estimation of a single seta during a parallel pull. To measure force parallel and perpendicular to the surface, we used a micromachined, dual-axis piezoresistive cantilever[7] fabricated on single-crystalline silicon wafers (Fig. 1e). It had two independent force sensors, each with one predominant direction of compliance. The perpendicular force sensor consisted of a thin triangular probe. The parallel force sensor was composed of four long slender ribs. A special 45° oblique ion implantation allowed piezoresistive and conductive regions to be implanted on both the parallel and perpendicular surfaces simultaneously. Forces applied to the tip of the sensor were resolved into these two orthogonal directions (parallel and perpendicular), and were measured by the changes in resistance of the piezoresistors. The minimum detectable force for these cantilevers, calculated from the noise spectra, is ~5nN in a 10kHz bandwidth. Maximum force measurements possible exceed 300 µN. The spring constant of the sensor was calibrated using a commercial force calibration cantilever (ThermoMicroscopes). The displacement sensitivity (dR/R per unit deflection of the cantilever) was obtained by measuring the resistance change of the piezoresistors while deflecting the cantilever by a known distance. Since this device was originally designed for AFM data storage applications, each of these cantilever devices had a sharp tip near the vertex of its triangular probe. For the gecko setae adhesion measurement, the back-side of this device was used to provide a smooth surface for setal adhesion.

Each seta was brought in contact with the sensor by applying a small preload perpendicular to the surface to increase contact and induce adhesion. To determine the effect of preload force on submaximal parallel force, we varied preload force when setae were attached to the tip of the sensor (Fig. 2b). To measure maximal parallel force, we used the base of the triangular probe. Using the base increased area of contact, but did not allow for simultaneous measurement of preload forces. Sensor signals were taken while the seta was being pulled parallel to the surface by a piezoelectric manipulator at a rate of ~5 μm sec^{-1}. Sensor signals were amplified and filtered through a 300-Hz low-pass filter, and then digitized at 100 Hz using a 16-bit data acquisition card (LabView™ on a PC). The collected data (in volts) were converted to deflections of the sensor through the displacement sensitivity, and multiplied by the spring constant to obtain force values.

Force estimation of a single seta during a perpendicular pull. Breaking or detachment force was defined as the maximal force a seta could exert perpendicular, or normal, to a surface immediately before it released. We determined this value for individual seta by measuring the amount it could displace a force gauge made from a 4.7 mm aluminum bonding wire with 25 μm nominal diameter (American Fine Wire Corp., Selma, AL; Fig. 1f). To maximize contact area of the active surface of the seta to the wire, we flattened a 50 μm x 100 μm section on the wire tip. The proximal end of the wire was fixed with epoxy onto a brass stub. We pressed the active surface of the seta against the flattened wire, producing a known perpendicular preload (1.6 μN ± 0.25 SD). We measured the force produced by the seta using two different methods of detachment: (1) we pulled the seta normal to the wire; and (2) we displaced the insect pin 19.7 μm ± 3.45 SD along the wire to produce an additional parallel preload on the seta before pulling perpendicular or normal to the wire.

In all trials, detachment force was calculated from the maximum displacement of the wire pulled by the seta. All sequences were recorded with a video camera (Sony CCD) and digitized to a computer (Apple, Macintosh) using a video editing system (Media 100 Inc., Marlboro, MA). The initial position of the wire, the angle of the seta with respect to the wire (α) and the position of the wire at the point of separation were recorded and analyzed using image analysis software (NIH-Image). The amount of deflection in the force gauge was converted to adhesion force after we calibrated the force gauge against standard weights.

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Figure 1 **a.** Tokay gecko (*Gekko gecko*) with toe outlined. SEMs of **b.** rows of setae from a toe, **c.** a single seta and **d.** the finest terminal branches of a seta, called spatulae. **e.** Single seta attached to a micro-electromechanical system (MEMS) cantilever[7] capable of measuring force production during attachment parallel and perpendicular to the surface. **f.** Single seta attached to an aluminum bonding wire making an angle (α) capable of measuring force production during detachment perpendicular to the surface.

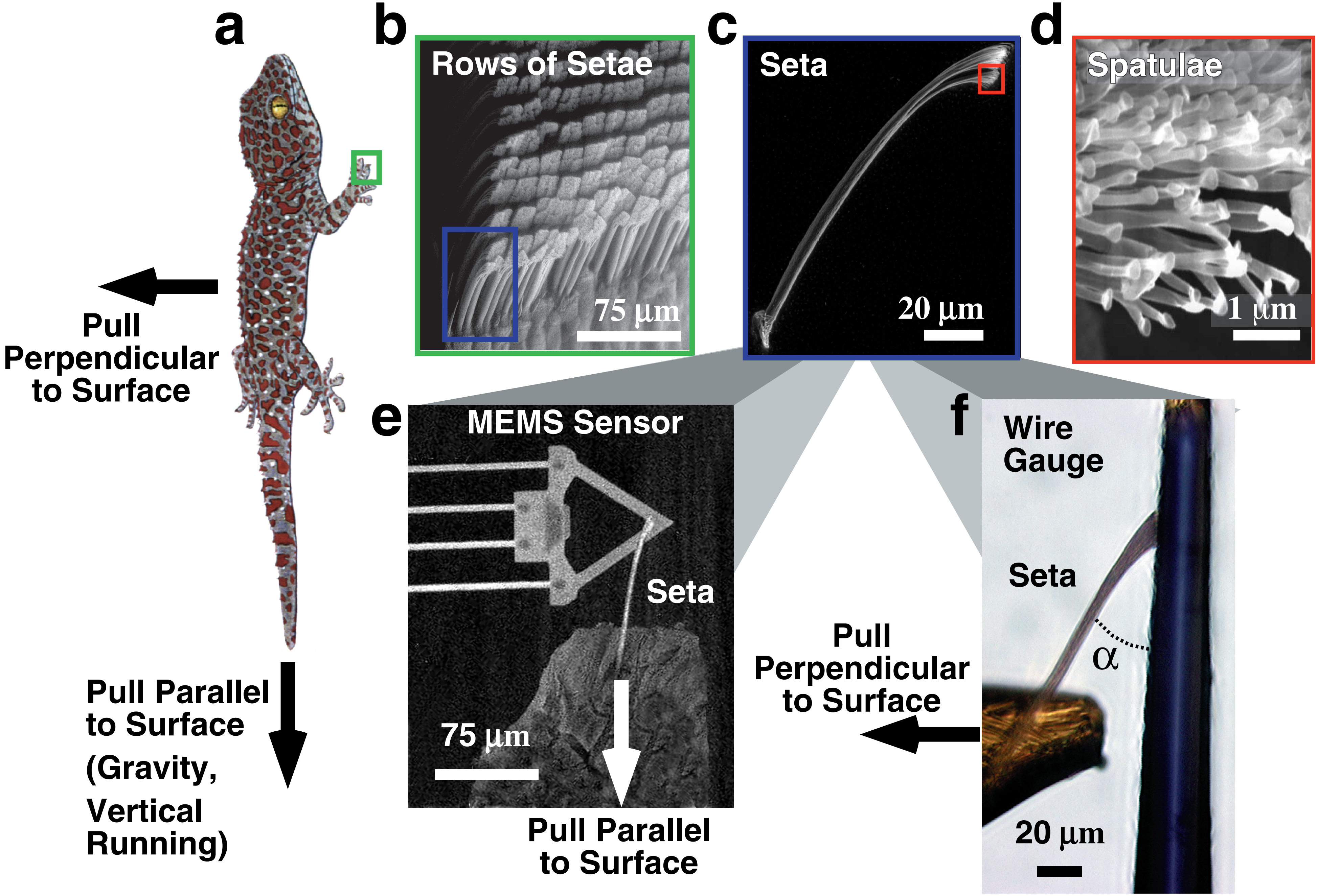
Figure 2. Force of single seta parallel to the surface with a known perpendicular preload. **a.** Submaximal force (solid line) as a function of time. Perpendicular preload is designated by the dashed line. t_s represents the time when the seta began to slide off the sensor. The initial perpendicular force need not be maintained during the subsequent pull. Diagrams show the stages of setal movement corresponding to the force record. Arrows indicate the direction of applied force to the seta. Vertical arrow indicates a parallel force, and a horizontal arrow indicates a perpendicular force. Parallel force was zero prior to force application, and both parallel and perpendicular forces return to zero following force application. **b.** Setal force parallel to the surface during attachment as a function of perpendicular preload force. Setal force was taken to be the adhesive force at the time just prior to sliding (t_s). The solid line represents a seta with spatulae projecting toward the surface. Results from a single seta are shown (parallel force = 2.8 perpendicular preload + 10.1; $r^2 = 0.74$; N = 41; F = 113; df = 1,39; $p < 0.0001$), but did not differ significantly in slope (ANCOVA, F = 2.1; df = 4,57; p = 0.10) or intercept (F = 0.052; df = 4,57; p = 0.99) among five setae. The dashed line represents the setal force with spatulae projecting away from the surface (parallel force = 0.25 perpendicular preload — 0.09; $r^2 = 0.64$; F = 13; df = 1,9; p = 0.007). The force produced by the inactive, non-spatular region increased with normal or perpendicular force, typical of materials with a coefficient of friction equal to 0.25. The perpendicular preloading force that could be applied attained a maximum (near 15 N), because greater forces resulted in the setal buckling.

Figure 3. Force of single seta parallel to the surface as a function of time. Diagrams show the stages of setal movement corresponding to the force record. Arrows indicate the direction of

applied force to the seta. Vertical arrow indicates a parallel force, and a horizontal arrow indicates a perpendicular force. Maximum force after a maximum preload (≈15 N). Data collected on MEMS cantilever (Fig. 1e).

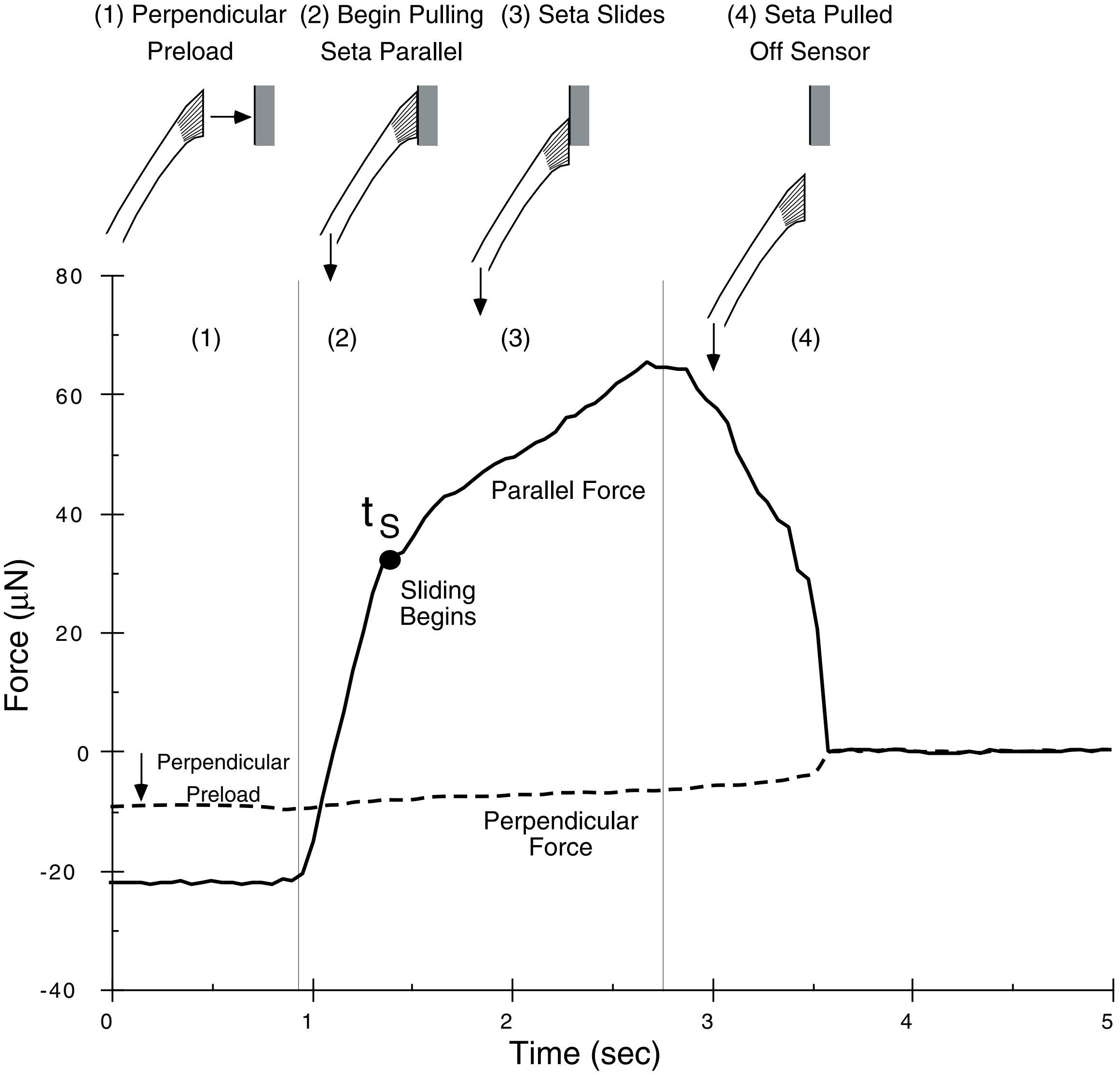
Figure 4. Setal angle (α) with the surface at detachment as a function of perpendicular force. Filled symbols represent seta pulled away from the surface until release. Open symbols represent seta held at a constant force as angle is increased. Each symbol shape represents a different seta. Data collected with wire gauge (Fig. 1f). Perpendicular force had a weak but significant effect on angle at detachment (α = 0.22 perpendicular force + 28.2; $r^2 = 0.25$; F = 20; df = 1,59; $p < 0.0001$).

Fig. 1



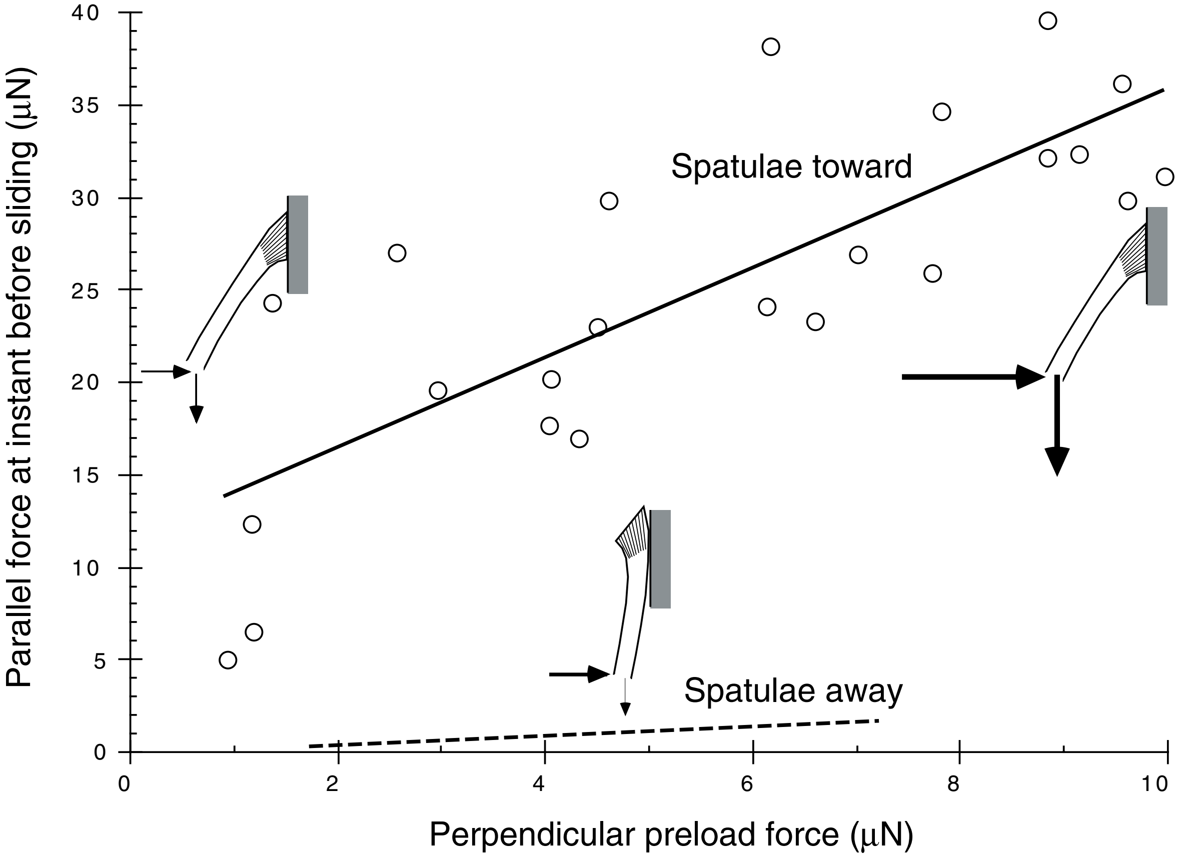
a
Pull Perpendicular to Surface
Pull Parallel to Surface (Gravity, Vertical Running)
b
Rows of Setae
75 µm
c
Seta
20 µm
d
Spatulae
1 µm
e
MEMS Sensor
Seta
75 µm
Pull Parallel to Surface
f
Wire Gauge
Seta
α
Pull Perpendicular to Surface
20 µm

Fig. 2A



(1) Perpendicular Preload
(2) Begin Pulling Seta Parallel
(3) Seta Slides
(4) Seta Pulled Off Sensor
(1)
(2)
(3)
(4)
80
60
40
20
0
-20
-40
Force (μN)
0
1
2
3
4
5
Time (sec)
t_S
Sliding Begins
Parallel Force
Perpendicular Preload
Perpendicular Force

Fig. 2B



Parallel force at instant before sliding (μN)
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
Perpendicular preload force (μN)
Spatulae toward
Spatulae away

Fig. 3

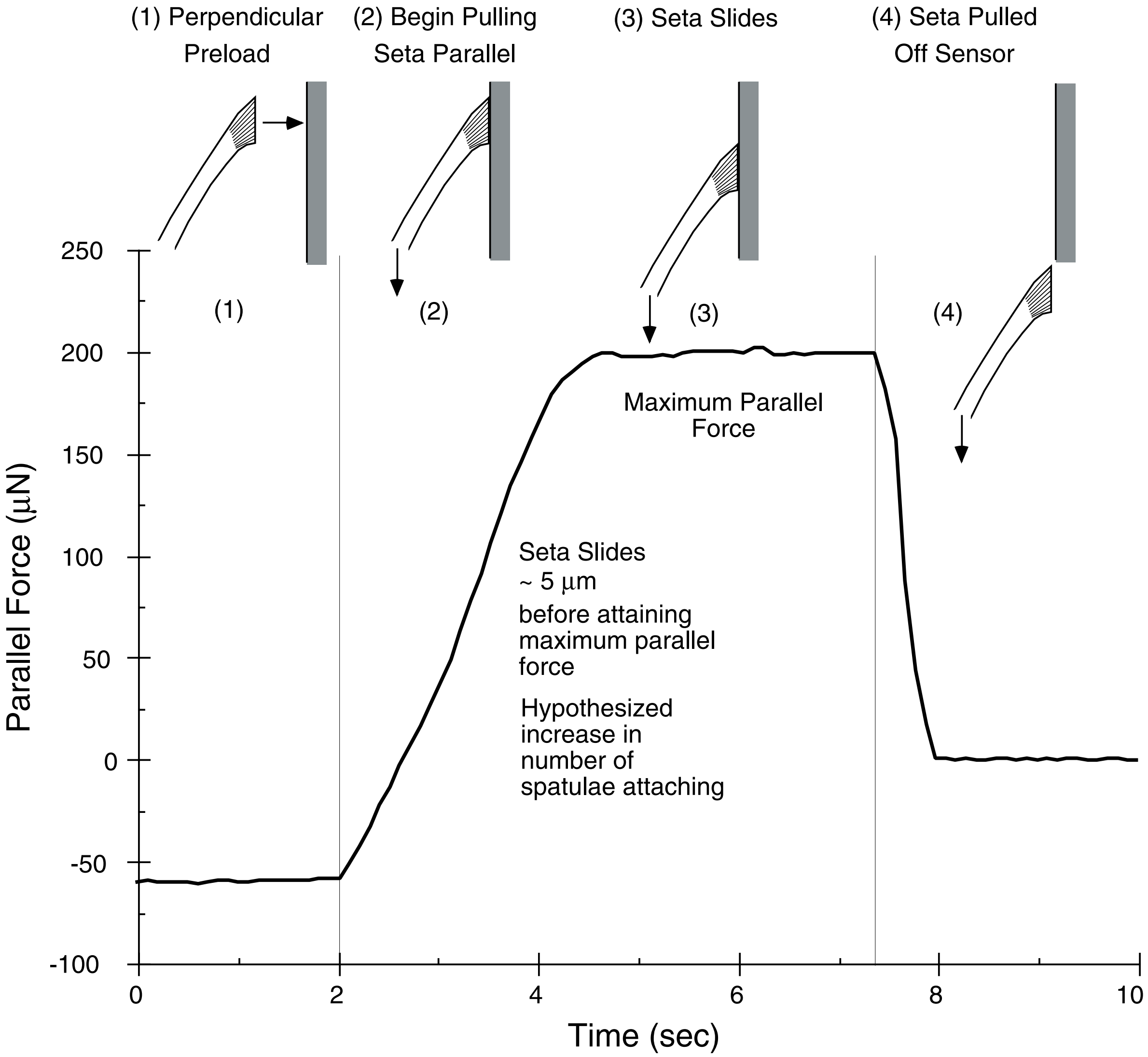
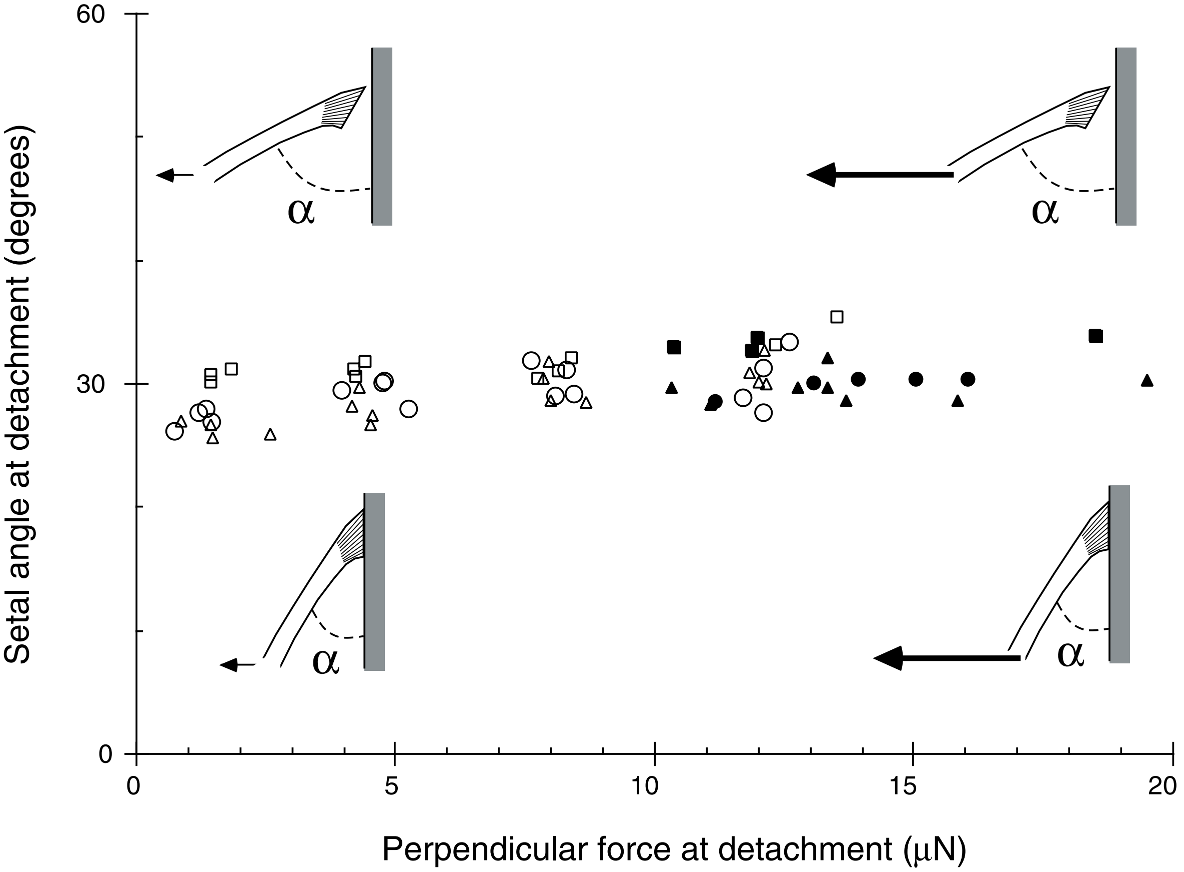

(1) Perpendicular Preload
(2) Begin Pulling Seta Parallel
(3) Seta Slides
(4) Seta Pulled Off Sensor
(1)
(2)
(3)
(4)
Maximum Parallel Force
Seta Slides ~ 5 μm before attaining maximum parallel force
Hypothesized increase in number of spatulae attaching
Parallel Force (μN)
250
200
150
100
50
0
-50
-100
Time (sec)
0
2
4
6
8
10

Fig. 4


60
30
0
0
5
10
15
20
Setal angle at detachment (degrees)
Perpendicular force at detachment (μN)
α
α
α
α