**Supplementary Material**

**S1: Cuticle Morphology**

To measure cuticle thickness (CT, cm) and areal porosity (AP, %), we used a scalpel to cut three thin cross sections from the femur of the second right leg of each individual (Figure 1); we standardized the leg and leg segment to control for any potential morphological variation in cuticle thickness across the body of the animal. Each cross section was mounted under a compound microscope (Olympus BX41TF, OPtical ELements COrportation, Dulles, Virginia, USA) with an attached camera (Q Color 3, Olympus America, Pennsylvania, USA) and imaged using the Qcapture program (version 2.9.13, Quantitative Imaging Corporation, Surrey, B.C., Canada). Within each image, cuticle thickness was measured at three haphazardly chosen points as the distance from the outer to the inner surface. Measurements were not taken where the cuticle appeared anomalously thick or thin, for example near apodemes. Cuticle thickness was calculated for each individual by averaging the three CT measurements from three pictures of each cross section from three cross sections of the femur (27 measurements per animal). These measurements were multiplied by 1.05 for *C. megalonyx* and 1.06 for *A. glacialis* to correct for our observation that femur CT was slightly thinner, on average, than the cuticle of other leg segments. Because the cuticle of the femur was slightly thinner than the cuticle of some of the other leg segments, we derived a correction factor for each species based on the difference between cuticle thickness of the femur vs. the cuticle thickness of the rest of the legs, and the relative lengths of each leg segment. First, we measured the cuticle thickness of each segment of all eight legs of two individuals from each species as above (3 measurements from 3 thin slices of each leg segment). We then measured the length of each segment of each leg (Lsegment) and calculated the proportional length of each segment relative to the entire leg (= Lsegment/Lleg), multiplied this proportion by the CT for that segment (=CTsegment x (Lsegment/Lleg), and calculated an average CT of the entire leg by summing the products across each leg (CTleg = Σ CTsegment x (Lsegment/Lleg). This sum was then divided by the measured CT of the femur of that leg to get our correction factor (CF = CTaverage/CTfemur). The correction factors from individuals were then averaged to get a correction factor for each species. This correction factor was then applied to the original measurements of the femur and used for all subsequent calculations (CTcorrected = CTfemur x CF).

To calculate areal porosity (AP) (the total cross-sectional area that is void space divided by the total area of the cuticle, *sensu* Nimmo 2004), we measured the total area of pores within each cross section and then divided that area by the total area of the cross section, and calculated an average AP for each individual as above for CT.

Surface area (cm2) was estimated by summing the area inside the projected outline of each spider and multiplying by two to account for the dorsal and ventral sides of the animal, then assumed the body was a long cylinder and multiplied this number by a correction factor of 1.57 to account for the three-dimensionality of the body. Then, to take into account the three-dimensionality of the animal’s body, we assumed the body to be a long open cylinder with a surface area equal to SA open cylinder = 2πr1hsegment, where r1 is the radius and h is the length of a leg segment. To convert from two to three dimensions, we multiplied the two-dimensional estimate from each animal by a correction factor of 1.57, which was derived from the relationship between the surface area of a two-dimensional rectangle (SArectangle=2 x 2rh) of the same diameter and length and the surface area of an open cylinder: = . Thus, SA3D=1.57 x SA2D, where SA2D was the surface area found using ImageJ (as in Lane et al. 2018).

To obtain the total volume of pores in each individual, we first calculated the cuticle volume as a hollow cylinder where htotal was the total summed length across all legs, r1 was the radius of the entire leg, and r2 was the radius of the inner hollow part of the leg. Pore volume was then calculated as the product of cuticle volume and areal porosity (PV = CV \* AP).

**S2:**

**Table 1.** Zero-inflated generalized linear mixed-effect model (ZIGLMM) of pycnogonid righting performance.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Species | n | Estimate ±SE | z | p |
| *Colossendeis* sp*.* |  |  |  |  |
| Temperature | 42 | -0.128 ±0.007 | -18.99 | <0.0001\* |
| Mass |  | 0.198 ±0.256 | 0.77 | 0.44 |
| Temperature\*Mass |  | -0.002 ±0.012 | -0.17 | 0.86 |
|  |  |  |  |  |
| *Colossendeis megalonyx* |  |  |  |  |
| Temperature | 20 | -0.116 ±0.015 | -7.92 | <0.0001\* |
| Mass |  | 1.510 ±0.489 | 3.09 | 0.002\* |
| Temperature\*Mass |  | 0.126 ±0.045 | 2.81 | 0.005\* |
|  |  |  |  |  |
| *Ammothea glacialis* |  |  |  |  |
| Temperature | 26 | -0.182 ±0.179 | -14.11 | <0.0001\* |
| Mass |  | -0.245 ±0.155 | -1.58 | 0.11 |
| Temperature\*Mass |  | 0.016 ±0.012 | 1.35 | 0.18 |

**S3:**

**Table 2.** Range and mean (±SE) number of rightings per hour (RPH) at each temperature treatment.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Species | Mass range (g) | Temperature °C | RPH range | Mean RPH (±SE) |
|  |  | -1.8 | 1 – 70 | 30.12 ±2.93 |
| *Colossendeis* sp*.* | 0.21 -21.80 | 4 | 0 – 101 | 26.26 ±22.45 |
|  |  | 7 | 0 – 40 | 11.75 ±14.44 |
|  |  | 9 | 0 – 23 | 3.57 ±5.21 |
|  |  | -1.8 | 1 – 63 | 20.20 ±3.92 |
| *Colossendeis megalonyx* | 0.21 – 2.26 | 4 | 0 – 54 | 14.45 ±3.67 |
|  |  | 7 | 0 – 34 | 16.0 ±6.51 |
|  |  | 9 | 0 – 11 | 1.90 ±0.70 |
|  |  | -1.8 | 14 – 75 | 48.19 ±3.14 |
| *Ammothea glacialis* | 0.18 – 2.22 | 4 | 0 – 49 | 25.39 ±2.75 |
|  |  | 7 | 0 – 46 | 8.27 ±1.98 |
|  |  | 9 | 0 – 12 | 2.19 ±0.74 |

**S4:**

**Table 2.** Range and mean (±SE) number of rightings per hour (RPH) at each temperature treatment.

|  |  |  |  |
| --- | --- | --- | --- |
| Species | Temperature °C | Mean RPH (±SE) | 95% CI |
|  | -1.8 | 30.12 ±2.93 | (24.21, 36.03) |
| *Colossendeis* sp*.* | 4 | 26.26 ±22.45 | (19.27, 33.26) |
|  | 7 | 11.75 ±14.44 | (2.58, 20.92) |
|  | 9 | 3.57 ±5.21 | (1.95, 5.20) |
|  | -1.8 | 20.20 ±3.92 | (11.99, 28.41) |
| *Colossendeis megalonyx* | 4 | 14.45 ±3.67 | (6.76, 22.14) |
|  | 7 | 16.0 ±6.51 | (-2.08, 34.08) |
|  | 9 | 1.90 ±0.70 | (0.44, 3.36) |
|  | -1.8 | 48.19 ±3.14 | (41.72, 54.67) |
| *Ammothea glacialis* | 4 | 25.39 ±2.75 | (19.71, 31.06) |
|  | 7 | 8.27 ±1.98 | (4.18, 12.36) |
|  | 9 | 2.19 ±0.74 | (0.66, 3.73) |

**S5:**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Table 3**. Scaling of cuticular morphology in pygnogonids. | | | | | | | | | |
| Models | | n | a | 95 % CI | P | b  (actual) | b (isometry) | 95 % CI | P | R2 |
| log(CT) vs log(Mass) | |  |  |  |  |  |  |  |  |  |
| *Colossendeis megalonyx* | | 24 | -2.26 | (-2.35,-2.17) | < 0.001 | 0.51 | 0.33 | (0.35,0.67) | <0.001 | 0.67 |
| *Ammothea glacialis* | | 27 | -2.21 | (-2.25,-2.17) | < 0.001 | 0.58 | 0.33 | (0.46,0.70) | <0.001 | 0.80 |
| log(SA) vs log (Mass) | |  |  |  |  |  |  |  |  |  |
| *Colossendeis megalonyx* | | 24 | 1.45 | (1.43,1.48) | <0.001 | 0.62 | 0.67 | (0.58,0.66) | <0.114 | 0.98 |
| *Ammothea glacialis* | | 27 | 1.31 | (1.29,1.33) | <0.001 | 0.78 | 0.67 | (0.73,0.83) | <0.001 | 0.98 |
| AP vs log(Mass) | |  |  |  |  |  |  |  |  |  |
| *Colossendeis megalonyx* | | 24 | 0.18 | (0.16,0.21) | <0.001 | 0.11 | - | (0.07,0.15) | <0.001 | 0.63 |
| *Ammothea glacialis* | | 27 | 0.10 | (0.09,0.11) | <0.001 | 0.05 | - | (0.03,0.07) | <0.001 | 0.52 |
| log(PV) vs log(Mass) | |  |  |  |  |  |  |  |  |  |
| *Colossendeis megalonyx* | | 24 | -1.62 | (-1.76,-1.48) | < 0.001 | 1.50 | 1 | (1.25,1.75) | <0.001 | 0.87 |
| *Ammothea glacialis* | | 27 | -1.93 | (-1.98,-1.87) | < 0.001 | 1.61 | 1 | (1.45,1.77) | <0.001 | 0.94 |
| "n": Number of individuals used in each analysis. Regression coefficients: intercept ("a"), scaling exponent calculated from the slope of the regression line (“b actual”), expected scaling exponent derived from geometric isometry (“b isometry). Expected scaling exponents for AP are unknown. | | | | | | | | | | |