Supplementary Materials and Methods

Minimal mechanical energetic cost in pitch and roll mode

To quantify how strenuous the pitch and roll modes are, we estimated the minimal mechanical energetic cost of the pitch or roll mode by calculating the maximal potential energy increase of the system during the traversal process using either mode.

For the pitch mode, we assumed that the animal kept a horizontal body orientation (zero body pitch and roll, neglecting legs), moved forward in the middle of the two beams with the lowest point of the body always contacting the ground, and pushed the beams down to traverse. The maximal potential energy increase of 7.9 mJ occurred when both beams deflected by nearly 90°.

For the roll mode, we assumed that the animal started with a horizontal body orientation and rolled by 90° to move through between the beams without deflecting them, with the lowest point of the body always contacting the ground. The maximal potential energy increase of 0.2 mJ occurred when the body roll was 90°.

S2. Pitch-to-roll transition barrier

The pitch-to-roll transition barrier can be calculated from the potential energy landscape model, and it is a function of the forward position x (Othayoth et al., 2020). In our previous study that used a simple ellipsoid to model the animal, when traversing beams of $K = 1.7$ mN·m·rad^{-1}, the pitch-to-roll transition barrier was 0.04 mJ at $x = -21$ mm where the animal was observed to transition ((Othayoth et al., 2020), Fig. 6B, iv), and it was 0.0021 mJ at $x = -13.6$ mm. In this study that used a refined animal model, when traversing beams of $K = 2.5$ mN·m·rad^{-1}, the pitch-to-roll transition barrier was 0.052 mJ at $x = -21$ mm,

and it was 0.0027 mJ at $x = -13.6$ mm where the animal transitioned. These similar values between the two studies demonstrated that our potential energy landscape approach is consistent and useful either with the simplest or refined animal model.
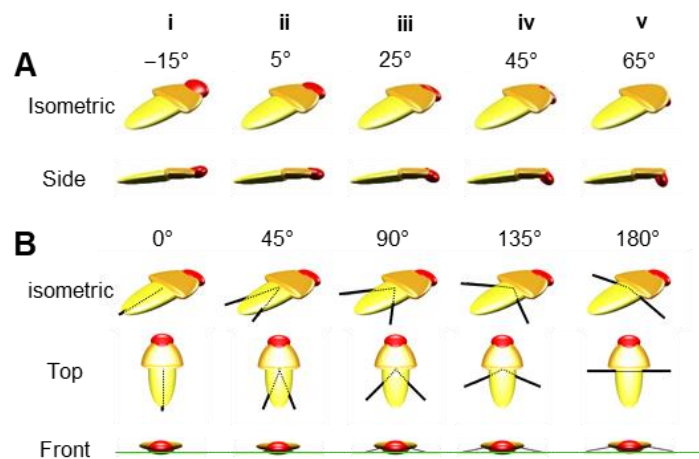
Fig. S1. Example variation of head flexion and total leg sprawl to test the use of head and leg adjustments in potential energy landscape model. (**A**) Head flexion. (**B**) Total leg sprawl. Green line in (**B**) front view is leg height = −5 mm.
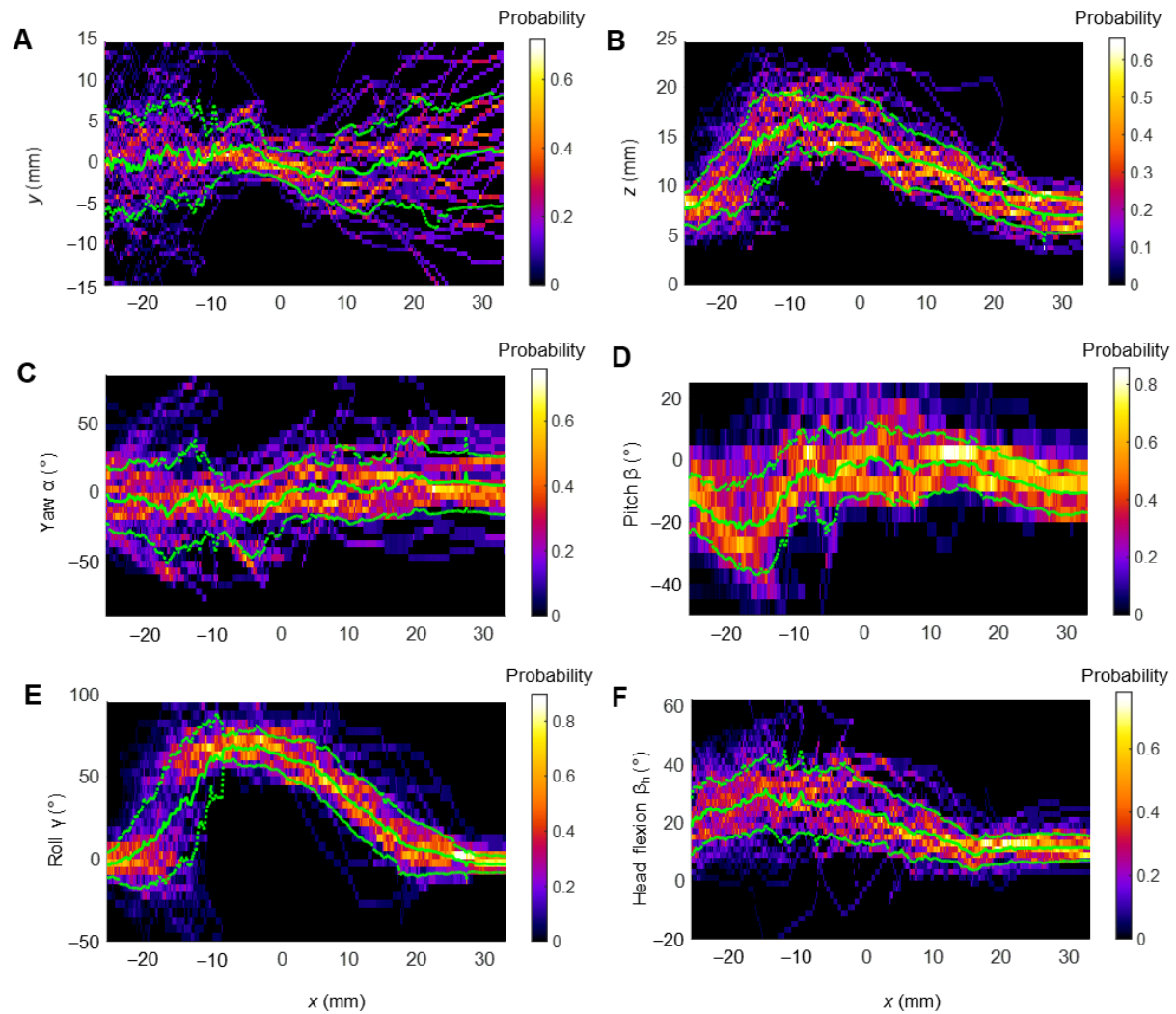
Fig. S2. Average trajectory as a function of forward position *x*. (**A**) Lateral position *y*. (**B**) Vertical position *z*. (**C**) Yaw α. (**D**) Pitch β. (**E**) Roll γ. (**F**) Head flexion β$_h$. Solid and dashed green curves are mean ± s.d. from averaging data of all trials. Each column of the heat map is a normalized histogram showing probability distribution of the data (sum of each column is 1) at corresponding forward position *x*.
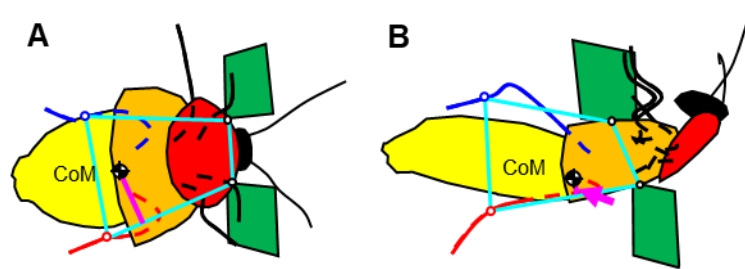
Fig. S3. Representative support polygon evolution from top view during pitch-to-roll transition. (**A**) Explore + pitch phases. (**B**) Roll phase. Cyan closed shapes show support polygons, and magenta lines show the distance from center of mass (CoM) to nearest lateral edge of the support polygon, which measures roll stability. In (**B**), the distance is small and indicated by a magenta arrow.
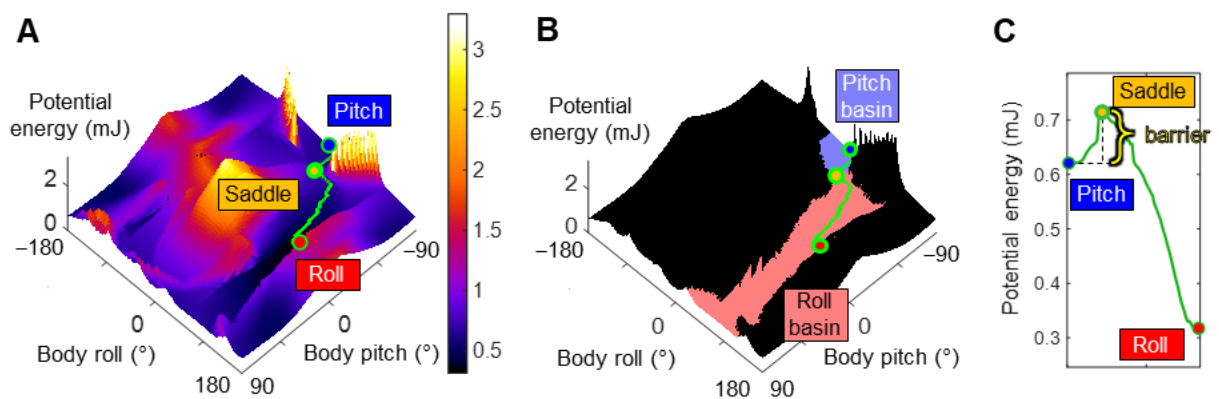
Fig. S4. Demonstration of breath-first search result on potential energy landscape. (**A**) Potential energy landscape pitch-roll cross section at $x = 0$ along the average animal trajectory, with hind legs neglected. Blue and red dots are pitch and roll local minima, respectively. Orange dot is saddle point. Green curve is imaginary route obtained from parent backtracking (Sec. 2.11). (**B**) Basins identified from breath-first search. Blue and red areas are pitch and roll basins, respectively. Boundary of basins is iso-height contour with the same potential energy as saddle point. Black area is rest of landscape. (**C**) Potential energy along imaginary route. Potential energy barrier is increase in potential energy from pitch minimum to saddle point. Note that imaginary route is only for defining saddle point, and during transition, animal did not necessarily start from a local minimum or transition by crossing saddle point.

Table S1. Ranges and increment of variables used in initial landscape variation (sweep) and the dimension collapse protocols used in subsequent pitch-roll and yaw cross-section analyses

| Variable	Unit	Min	Max	Increment	Dimension collapsing protocol	
					Pitch-roll cross-section	Yaw cross-section
Forward position x	mm	−26	33	0.2	Not collapsed	Not collapsed
Lateral position y	mm	−3	3	1	Follow average trajectory	Follow average trajectory
Vertical position z	mm	z_{min}	z_{min} + 1	1	Minimize potential energy	Minimize potential energy
Yaw α	deg	−90	90	5	Follow average trajectory	Not collapsed
Pitch β	deg	−90	90	2	Not collapsed	Follow average trajectory
Roll γ	deg	−180	180	2	Not collapsed	Follow average trajectory
Head flexion β_h	deg	−25	65	5	Not collapsed or follow average trajectory	Not collapsed
Abdomen flexion β_a	deg	7	7	-	-	-

z_{min}: vertical position z when the body touched the ground.

**Table S2. Frequently used averaged variables in landscape analyses**

Variable	Time range	Measured value	Used value
Forward position x	Pitch-to-roll transition	−13.6 ± 4.4 mm	−13.6 mm
Maximum leg length	Explore + pitch and roll phase	27 ± 2 mm	27 mm
Temporal averaged abdomen flexion β_a	Approach phase	7° ± 4°	7°
Head flexion range β_h	Whole trial	[−24°, 64°]	-
Temporal averaged head flexion β_h	Approach phase	15° ± 4°	15°
Temporal averaged leg height	Explore + pitch phase	−5 ± 3 mm	−5 mm
Maximal total leg sprawl ϕ_T	Explore + pitch phase	156° ± 21°	160°
Minimal total leg sprawl ϕ_T	Roll phase	21° ± 17°	20°
Kinetic energy fluctuation	Explore + pitch and roll phase	0.01 ± 0.01 mJ	0.01 mJ
Temporal averaged forward position x	Explore + pitch phase	−20 ± 3 mm	−20 mm
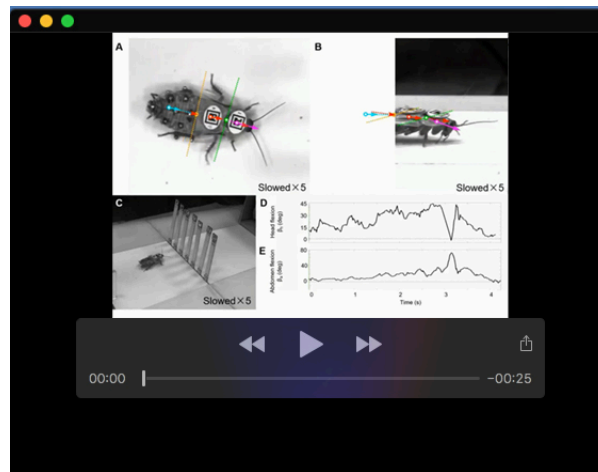
Movie 1. Head and abdomen flexion. Top: zoomed top (left) and side (right) views. White points with red, magenta, cyan, green, and orange edges are the origins of thorax frame, head frame, abdomen frame, middle point of thorax-head joint, and middle point of the thorax-abdomen joint, respectively. Solid and dotted arrows show $+x$ and $+x'$ direction of body (red), head (magenta), and abdomen (cyan) frames, respectively. Head and abdomen flexion are the angles between body $+x'$ direction and head or abdomen $+x$ direction. Bottom left: isometric view. Bottom right: head and abdomen flexion as a function of time.
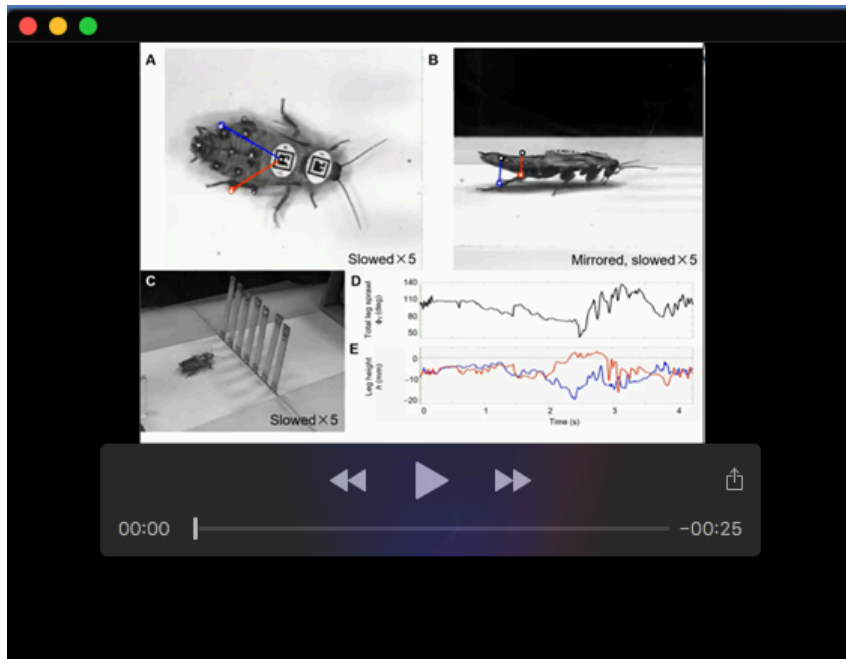
Movie 2. Leg adjustments. Top left: zoomed top view. White points with thick blue, red, and black edges are the left and right tibia-tarsal joints and origin of thorax frame, respectively. White points with thin blue and red edges are the projections of the tibia-tarsal joints into the body coronal plane. Total leg sprawl is the angle between the dashed blue and red lines. Top right: zoomed mirrored side view. White points with blue, red, and black edges are tibia-tarsal joints and their projections to body coronal plane, respectively. Leg height of left and right hind legs is opposite value of the length of the blue and red lines, respectively. Bottom left: isometric view. Note that this view is mirrored to better show leg motion. Bottom right: Leg sprawl (top) and leg height (bottom) as a function of time. Blue and red are for left and right hind legs, respectively.
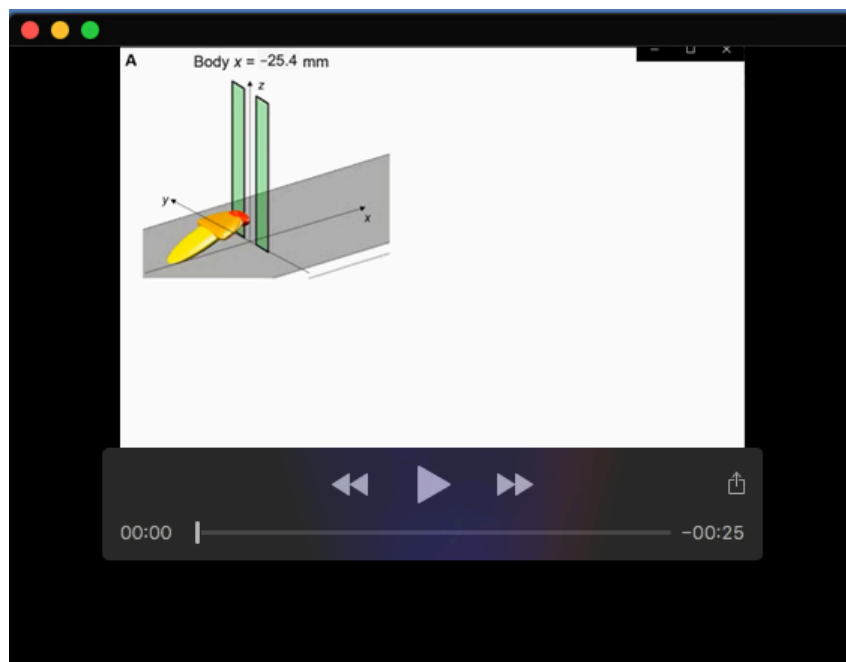
Movie 3. Potential energy landscape model. Part 1. Pitch-to-roll transition on pitch-roll cross section. Part 2. Roll-to-deflect transition on yaw cross section. Top left: model of cockroach traversing beam obstacles at head flexion $\beta_h = 15°$ with hind legs neglected. Top right: potential energy landscape pitch-roll cross section (part 1) or yaw cross section (part 2) along the average animal trajectory. Blue, red, and purple dots are pitch, roll, and deflect local minima, respectively. Orange dots are saddle points. Green curves are imaginary routes. Bottom left: Potential energy along the imaginary route. Bottom right: Potential energy barrier as a function of forward position x.