

1 **Title: Insect wings and body wall evolved from ancient leg segments**
2 **One Sentence Summary: CRISPR-Cas9 knockout of leg gap genes in a crustacean reveals**
3 **that insect wings are not novel structures, they evolved from crustacean leg segments**
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7

8 **Abstract: The origin of insect wings has long been debated. Central to this debate is**
9 **whether wings evolved from an epipod (outgrowth, e.g., a gill) on ancestral crustacean leg**
10 **segments, or represent a novel outgrowth from the dorsal body wall that co-opted some of**
11 **the genes used to pattern the epipods. To determine whether wings can be traced to**
12 **ancestral, pre-insect structures, or arose by co-option, comparisons are necessary between**
13 **insects and arthropods more representative of the ancestral state, where the hypothesized**
14 **proximal leg region is not fused to the body wall. To do so, we examined the function of five**
15 **leg patterning genes in the crustacean *Parhyale hawaiiensis* and compared this to previous**
16 **functional data from insects. By comparing gene knockout phenotypes of leg patterning**
17 **genes in a crustacean with those of insects, we show that two ancestral crustacean leg**
18 **segments were incorporated into the insect body, moving the leg's epipod dorsally, up onto**
19 **the back to form insect wings. Thus, our data shows that much of the body wall of insects,**
20 **including the entire wing, is derived from these two ancestral proximal leg segments. This**
21 **model explains all observations in favor of either the body wall origin or proximal leg**
22 **origin of insect wings. Thus, our results show that insect wings are not novel structures, but**
23 **instead evolved from existing, ancestral structures.**

24 **Main Text:** The origin of insect wings has fascinated researchers for over 130 years. One
25 theory proposes that the proximal portion of the ancestral crustacean leg became incorporated
26 into the body (*I*), which moved the leg's epipod (lobe-shaped outgrowth, e.g. gill) dorsally, up

27 onto the back to form insect wings (2). Another theory proposes that the wing is a novel
28 outgrowth from the dorsal body wall that co-opted some of the genes used to pattern the epipods
29 of leg segments (3). Alternatively, wings may be derived from a combination of leg and body
30 wall (dual origin, (4)). To determine whether wings can be traced to ancestral, pre-insect
31 structures, or arose by co-option, comparisons are necessary between insects and other
32 arthropods more representative of the ancestral state, where the hypothesized proximal leg region
33 is not fused to the body wall.

34 Towards this aim, we examined five leg gap genes, *Distalless (Dll)*, *Sp6-9*, *dachshund*
35 (*dac*), *extradenticle (exd)*, and *homothorax (hth)*, in an amphipod crustacean, *Parhyale*
36 *hawaiensis*. While we have documented their expression at several developmental stages (Fig.
37 S1), our comparative analysis does not rely solely on these expression patterns, given that
38 expression is not always a reliable indication of function, and expression is often temporally
39 dynamic (5). Instead, we have systematically knocked out these genes in *Parhyale* using
40 CRISPR- Cas9 mutagenesis and compared this to our understanding of their function in
41 *Drosophila* and other insects (Figs. 2, S2).

42 Insects have six leg segments, while *Parhyale* has seven (Fig. 1). In insects, *Dll* is
43 required for the development of leg segments 2 – 6 (6-9) . In *Parhyale*, the canonical *Dll* gene,
44 *Dll-e (10-12)*, is required for the development of leg segments 3 – 7 (Fig. 2b). In insects, *Sp6-9*
45 (*13*) is required for the development of leg segments 1 – 6 (*14*), and in addition in *Drosophila*,
46 loss of *Sp6-9* (i.e. D-Sp1, (*13*)) occasionally transforms the leg towards wing and lateral body
47 wall identity (*14*). In *Parhyale*, *Sp6-9 (13, 15)* is required for the development of leg segments 2
48 – 7 (Fig. 2c), and in some legs, segment 2 is occasionally transformed towards a leg segment 1
49 identity (Fig S3). In *Drosophila*, *dac* is required in the trochanter through proximal tarsus (leg

50 segments 2 – 4, and first tarsus, (15, 16). *Parhyale* has two *dac* paralogs. *dac1* does not seem to
51 be expressed in the legs or have a morphologically visible knockout phenotype. *dac2* is required
52 to pattern leg segments 3 – 5 (Fig. 2d). *exd* and *hth* are expressed in the body wall and proximal
53 leg segments of insects (17-20) and *Parhyale* (21) (Fig S1). They form heterodimers and
54 therefore have similar phenotypes (17-20). In insects, *exd* or *hth* knockout results in
55 deletions/fusions of the coxa through proximal tibia (leg segments 1 – 3, and proximal tibia, 17-
56 20). In *Parhyale*, *exd* or *hth* knockout results in deletions/fusions of the coxa through proximal
57 carpus (leg segments 1 – 4, and proximal carpus; Figs. 2e, f). In both insects (17, 18, 22) and
58 *Parhyale*, the remaining distal leg segments are sometimes transformed towards a generalized
59 thoracic leg identity (compare Fig. 2 e, f and Fig S4). In both insects (17-20) and *Parhyale* (Fig.
60 S4), *exd* or *hth* knockout results in deletions/fusions of body segments.

61 In summary, the expression and function of *Dll*, *Sp6-9*, *dac*, *exd*, and *hth* in *Parhyale* are
62 shifted distally by one segment relative to insects. This shift is accounted for if insects fused an
63 ancestral proximal leg segment into the body wall (Fig. 2g). Thus, there is a one-to-one
64 homology between insect and *Parhyale* legs, displaced by one segment, such that the insect coxa
65 is homologous to the crustacean basis (23), the insect femur is the crustacean ischium, and so on
66 for all leg segments. This also means that part of the insect body wall is homologous to the
67 crustacean coxa.

68 Clark-Hachtel (accompanying manuscript) show that the plates on the *Parhyale* basis,
69 coxa, and lateral body wall are epipods. The body wall epipod is notable, because epipods are
70 characteristic of leg segments (23). This suggested to us that part of the *Parhyale* body wall
71 might actually be an additional leg segment. In fact, most groups of crustaceans have an
72 additional proximal leg segment, the precoxa (Fig. 3a). To determine whether *Parhyale* retains

73 the precoxa, we examined dissected *Parhyale* using confocal and brightfield microscopy. We
74 identified a precoxal structure that meets the criteria for a true leg segment: it protrudes
75 conspicuously from the body wall; it forms a true, muscled joint; and it extends musculature to
76 another leg segment (Figs. 3 and S5, (23-25)). Importantly, the plate does not emerge from the
77 body wall, but from the precoxa (Fig. 3e), like the plates of the coxa and basis. Thus, much of
78 what appears to be lateral body wall in *Parhyale* is in fact proximal leg.

79 If the insect coxa is homologous to the crustacean basis, what happened to the leg
80 segments corresponding to the ancestral crustacean precoxa and crustacean coxa in insects? If
81 these two leg segments became incorporated into the body wall, then one would expect to find
82 two leg segments and two epipods dorsal to the insect coxa (Fig. 4a). As predicted, two leg-like
83 segments can be observed proximal to the coxa in basal hexapods (*I*) including collembolans
84 (26), as well as in the embryos of many insects (27-29), where these two leg-like segments
85 flatten out before hatching to form the lateral body wall (*I*, 26-31). Insects also appear to have
86 two epipods dorsal to the insect coxa, because when “wing” genes are depleted in insects via
87 RNAi, two distinct outgrowths are affected, the wing and the plate adjacent to the leg (Fig. 1c,
88 (32-35)).

89 Based on these data, insects incorporated two ancestral leg segments, the precoxa and
90 crustacean coxa, into the body wall (Fig. 4a). Thus, like *Parhyale*, much of what appears to be
91 lateral body wall in insects is in fact proximal leg. Clark-Hachtel’s interpretation of the dual
92 origin theory proposes that these two leg segments and their two epipods fused to form the wing.
93 While we agree that both leg segments may contribute wing muscle, we propose that only the
94 more dorsal precoxa epipod formed the insect wing, while the more ventral crustacean coxa
95 epipod formed the insect plate (Fig. 4b).

96 Our results may settle the long-standing debate regarding the origin of insect wings as
97 derived from either an epipod of the leg or from body wall. Our model accounts for all
98 observations in favor of either of these hypotheses, including the dorsal position of insect wings
99 relative to their legs, the loss of ancestral leg segments in insects, the two-segmented
100 morphology of the insect subcoxa in both embryos and adults, the complex musculature for
101 flight, and the shared gene expression between wings and epipods. Our model also explains the
102 apparent “dual origin” of insect wings from both body wall and leg epipod: much of what
103 appears to be insect body wall is in fact the remnant of two ancestral leg segments and their
104 epipods.

105 In fact, a number leg-associated outgrowths in arthropods could be explained by this
106 model, in addition to insect wings. The *Daphnia* carapace(36) is the epipod of the precoxa(37);
107 the *Oncopeltus* small plate outgrowth (Fig. 1c) is the epipod of the crustacean coxa; and the
108 thoracic stylus of jumping bristletails (Fig. 4, st) is the epipod of the crustacean basis(38, 39).
109 This also explains many insect abdominal appendages, like gills(40), gin traps(33), prolegs(41),
110 and sepsid fly appendages(42), which are often proposed as de novo structures(43-45). However,
111 most insects form abdominal appendages as embryos(40, 46), some even with an epipod nub, but
112 these fuse to the body wall before hatching to form the sternites(28, 39). The existence of insect
113 abdominal appendages is supported by a re-analysis of the expression of *Sp6-9* and its paralog,
114 *buttonhead*, in insect embryos in a previous study (13). According to the leg segment homology
115 model presented here (Fig. 4), the paired dots of *btd* expression on each abdominal segment of
116 insect embryos demonstrates that these appendages are comprised of three leg segments: the
117 precoxa (pink), crustacean coxa (red), and insect coxa (orange). These abdominal appendages are
118 truncated, lacking all distal appendages from the trochanter (yellow) down, because *Dll* and *dac*,

119 which mark the trochanter and more distal leg segments, are not expressed in the insect
120 abdomen. Thus, rather than de novo co-options, abdominal appendages were always there,
121 persisting in a truncated, highly modified state, and de-repressed in various lineages to form
122 apparently novel structures. This provides a model for how insect wings can be both homologous
123 to the epipod of the crustacean precoxa, and yet not be continuously present in the fossil record:
124 epipod fields may persist in a truncated state, perhaps only visible as a nub in the embryo. We
125 therefore propose cryptic persistence via truncation as a general mechanism for the origin of
126 apparently novel structures that appear to be derived from serial homologs, rather than the
127 current model of extensive gene co-option.

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240

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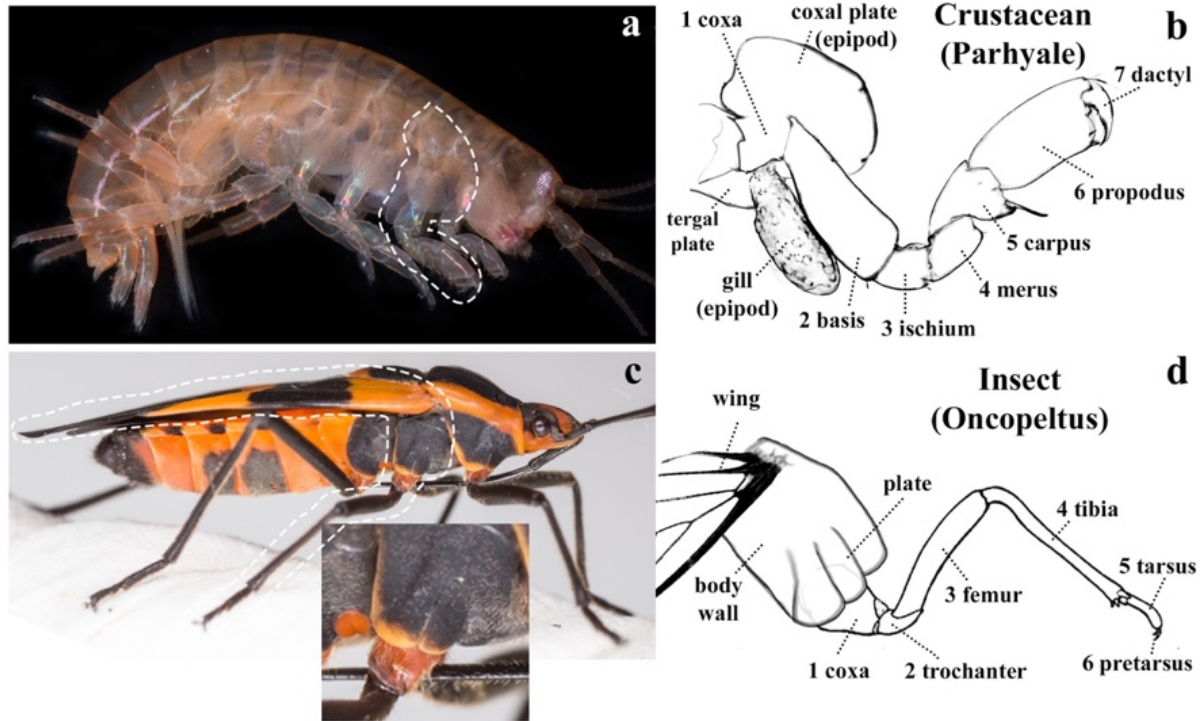
248 **Supplementary Materials:**

249 Materials and Methods

250 Figures S1-S5

251 Table S1

252 References 37-43



253

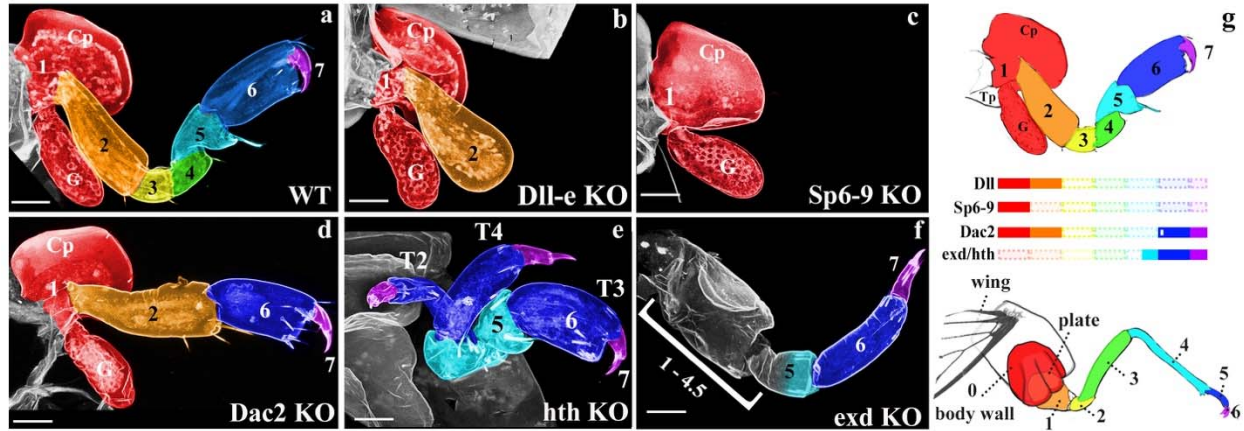
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255 Fig. 1. Crustacean and insect legs. (a) Adult *Parhyale*, with third thoracic leg (T3) outlined. (b)

256 Cartoon of *Parhyale* T3. The coxal plate extends over the leg. (c) Adult *Oncopeltus*, with T2

257 outlined. Inset shows magnified proximal leg, with body wall plate extending over the leg. (d)

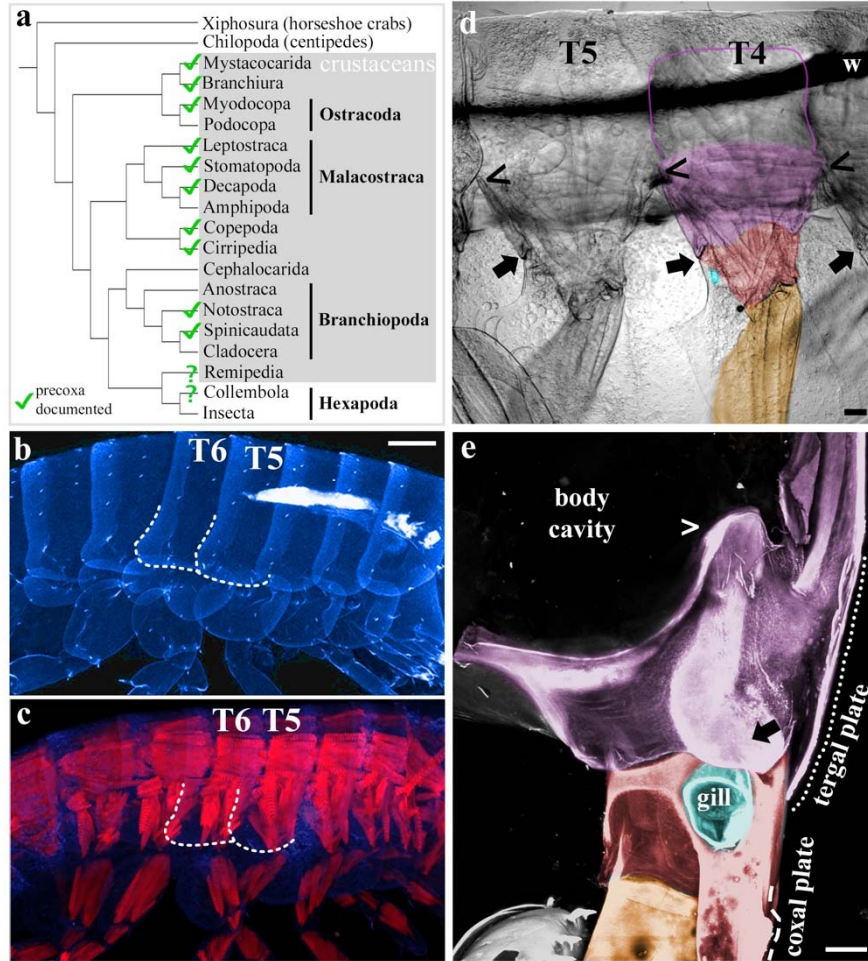
258 Cartoon of *Oncopeltus* T2 leg.



259

260 Fig. 2. Knockout phenotypes of leg gap genes. (a-f) *Parhyale* CRISPR-Cas9 phenotypes in
 261 dissected third thoracic legs (T3). Graded cyan in f indicates deletion/fusion of proximal leg
 262 segment 5. (g) Leg gap gene function in *Parhyale* and insects aligns only if insects incorporated
 263 the red leg segment into the body wall (0). Color bars correspond to remaining leg segments
 264 following knockout, transparent bars indicate deleted leg segments. Open bar in *dac* indicates
 265 slight extension of *dac* function into tarsus 1 of insects. Coxal plate (Cp), gill (G), tergal plate
 266 (Tp). Scale bar 50um.

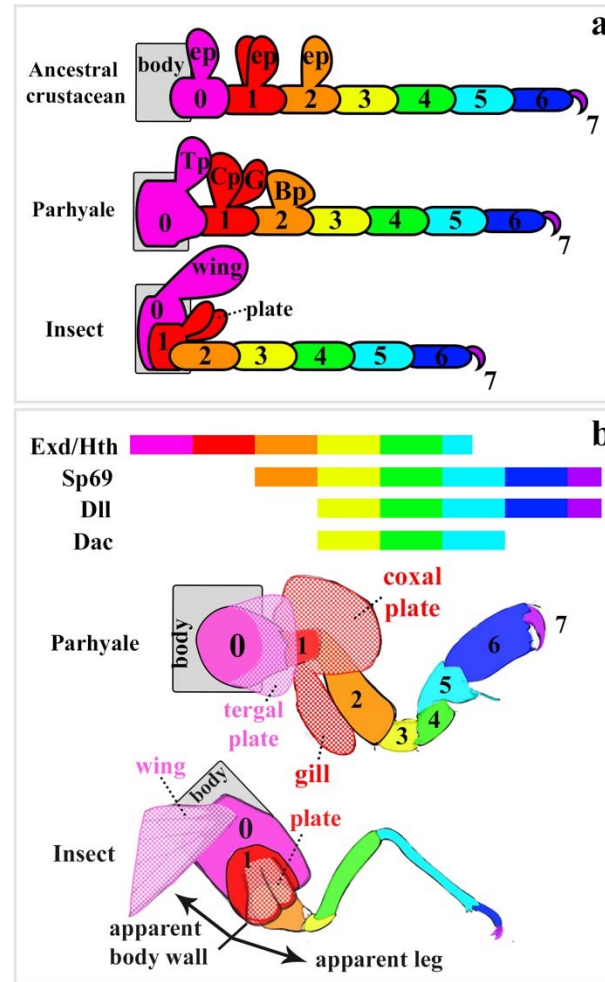
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268

269 Fig. 3. Evidence for a precoxa in *Parhyale*. (a) Phylogeny based on Oakley 2012, precoxa
 270 references in supplements. (b) Confocal image of *Parhyale* hatchling, autofluorescent cuticle in
 271 blue. T5, T6 tergal plates (dotted outlines). (c) Confocal image of *Parhyale* hatchling,
 272 autofluorescent cuticle in blue, muscle phalloidin stain in red. Compare blocks of simple,
 273 anterior-posterior muscles of the body to orthogonal, complexly arranged muscles of the leg
 274 segments. Note overlap between tergal plate (dotted lines) and orthogonal leg muscle. (d)
 275 Brightfield image of right half of *Parhyale*, sagittal dissection, internal tissues removed, lateral
 276 view. Wire used to position sample (w). The same orthogonal muscles in b are visible as
 277 striations extending above the wire. The precoxa forms a joint with the coxa (47) (arrow). The
 278 dorsal limit of the precoxa is unclear: a conservative estimate is to begin at the joint (arrow) and

279 follow the leg up to where it meets the adjacent leg, denoted by (<); however, the orthogonal
280 muscle striations continue farther up (pink outline). Either way, the precoxa protrudes quite a bit
281 from the body wall. (e) Posterior-lateral view of right T6, looking edge-on at tergal plate. The
282 tergal plate (dotted outline) emerges from the precoxa (contiguous pink between ←, >, and ---),
283 just as the coxal plate (dashed line) emerges from the coxa. In c, d, coxa is red (coxal plate not
284 shaded), gills (teal) partially cut for visibility, basis orange, precoxa pink. Note that all three
285 plates (tergal, coxal, and basal) form contiguous cuticle with their leg segment, i.e. there is no
286 distinguishing suture. Scale bar 100um.



287

288 Fig. 4. Proposed leg segment homologies (colors) between insects, *Parhyale*, and an ancestral
289 crustacean (a) based on gene function alignment (b). Ancestral precoxa epipod (pink ep),
290 *Parhyale* tergal plate (Tp), and insect wing are homologous (pink). Ancestral coxa epipod,
291 *Parhyale* coxal plate (Cp) and gill (G), and insect plate (see Fig. 1c) are homologous (red).
292 *Parhyale* basal plate (Bp). Insect numbering based on crustaceans.