October 16, 2025

Master Degree in Bionics Engineering

Course of Principles of Bionics and Biorobotics Engineering

Lesson title:

Bionic locomotion principles – Terrestrial legged locomotion

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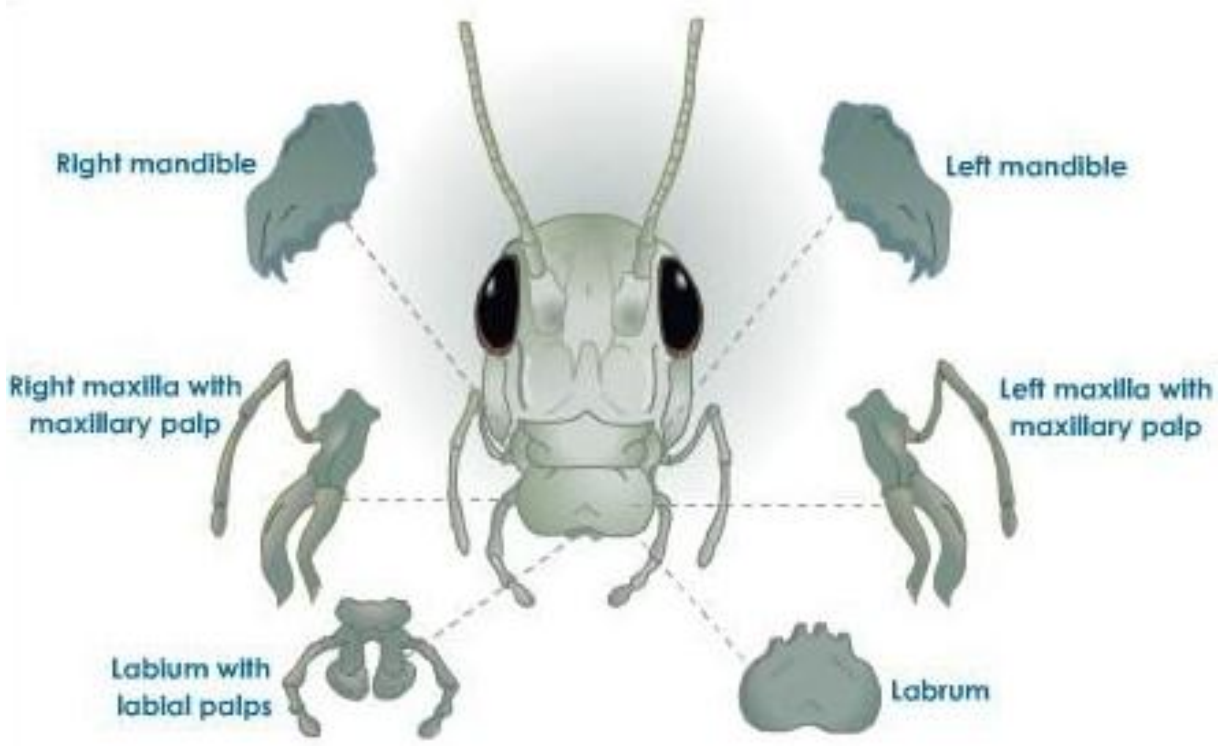
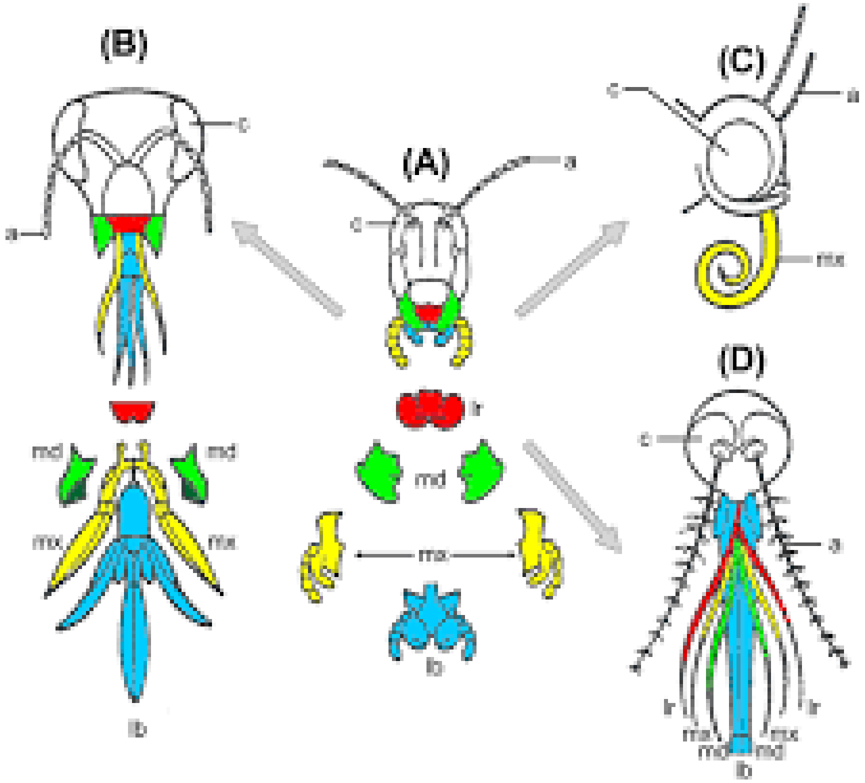
THE BIOROBOTICS INSTITUTE

Scuola Superiore Sant'Anna

Head


Right mandible
Left mandible
Right maxilla with maxillary palp
Left maxilla with maxillary palp
Labium with labial palps
Labrum


(B)
(A)
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md
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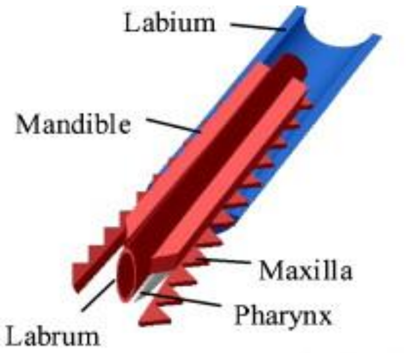
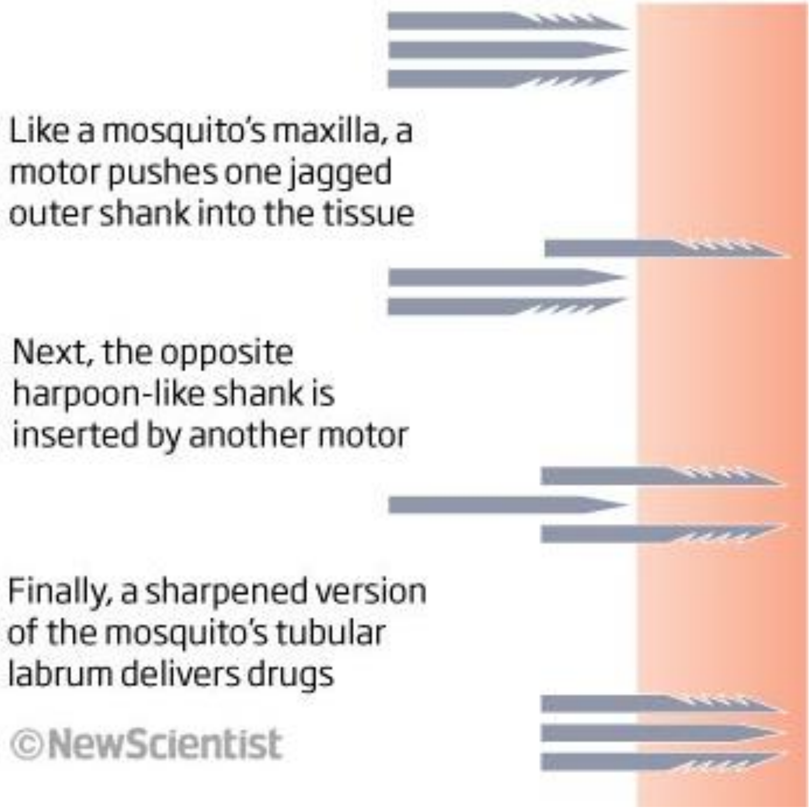
Mosquitoes inspired Needles

Ever notice how a mosquito can bite you without you even knowing it?

BIOLOGY:
A mosquito's proboscis includes an **internal tubular labrum** (that does the bloodsucking), which is sheathed between two serrated maxillae – one on either side. The **maxillae are what first penetrate** the skin and then sink into it, after which **the labrum slides down between them**. Because the maxillae have a jagged outer surface, they present a **minimum amount of surface area** to nerves in the skin.



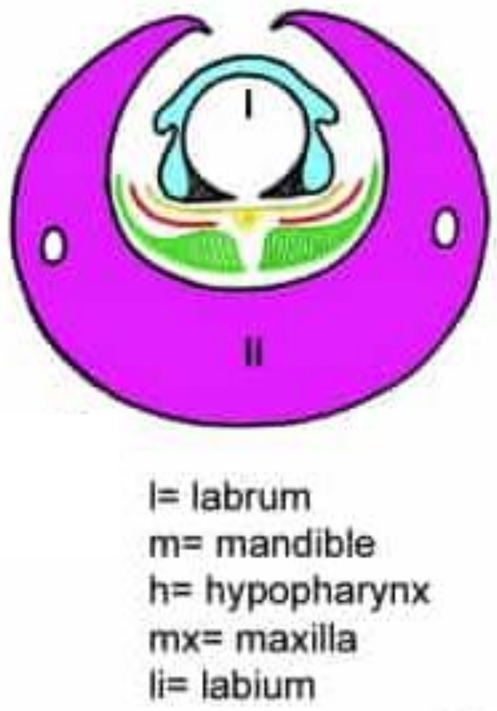


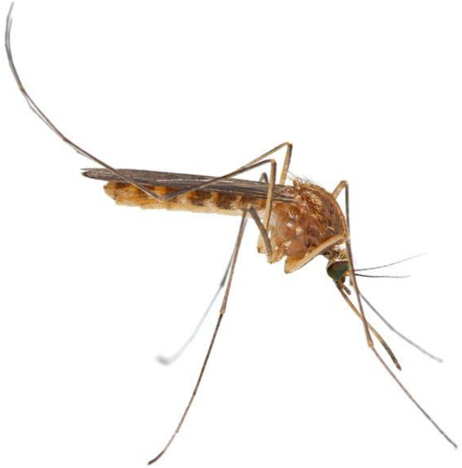
Izumi, H., Suzuki, M., Aoyagi, S., & Kanzaki, T. (2011). Realistic imitation of mosquito's proboscis: electrochemically etched sharp and jagged needles and their cooperative inserting motion. *Sensors and Actuators A: Physical*, *165*(1), 115-123.

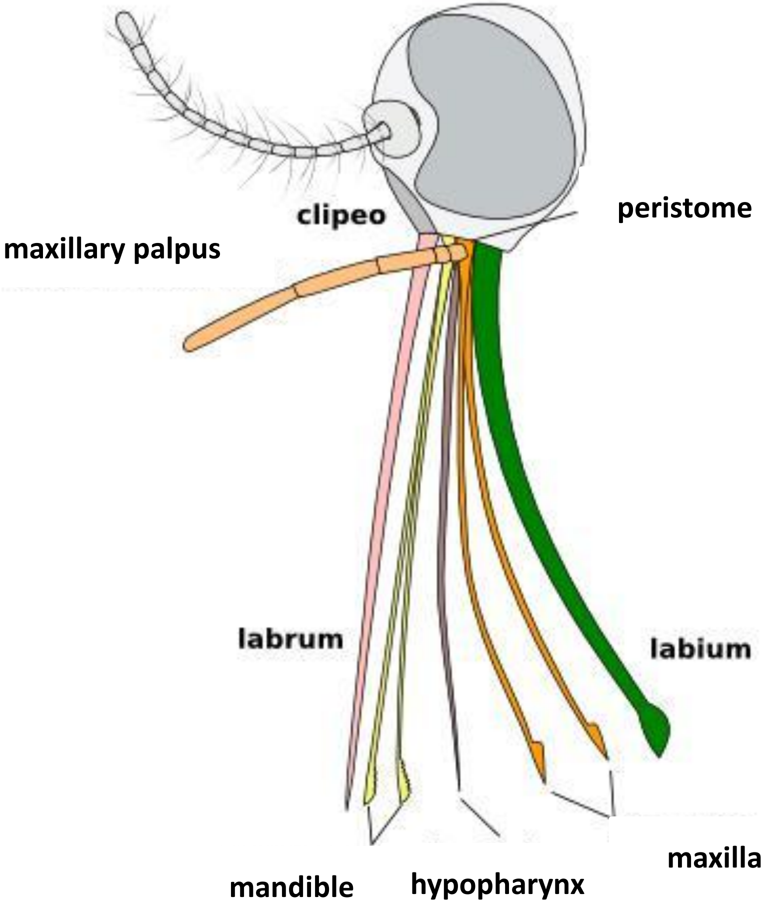
https://www.newscientist.com/article/mg20928044-900-mosquito-needle-helps-take-sting-out-of-injections/

Mosquitoes inspired Needles

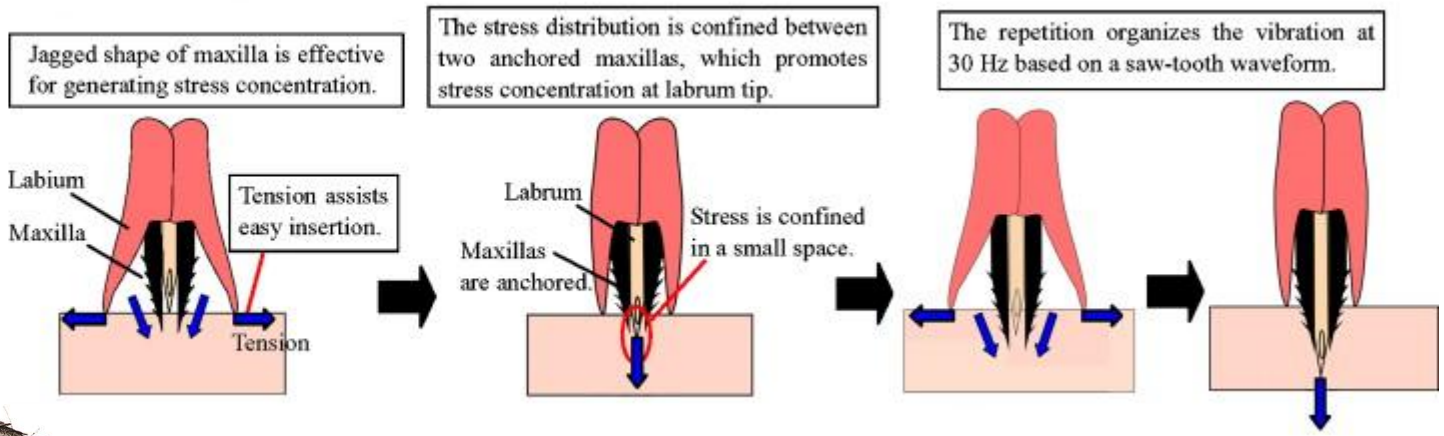
Ever notice how a mosquito can bite you without you even knowing it?

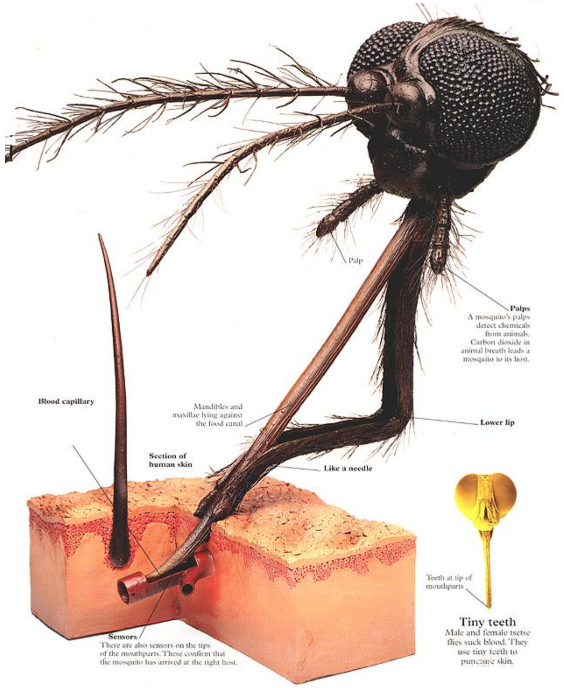


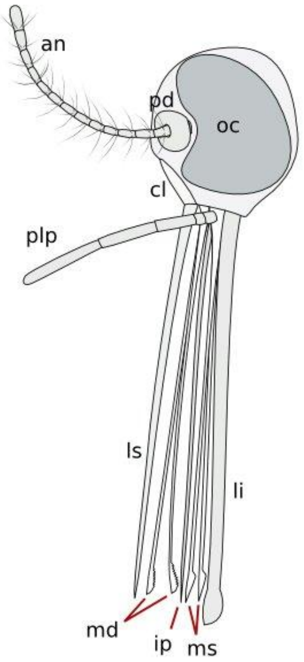




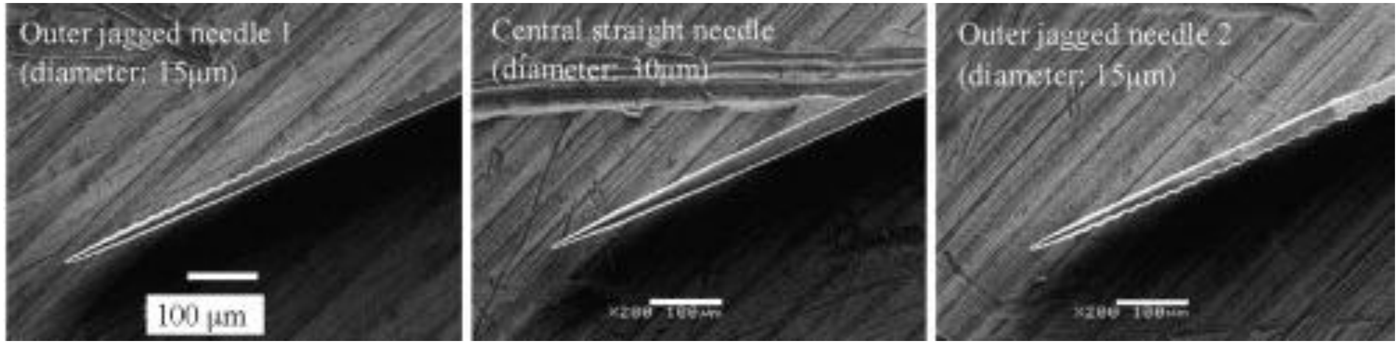
Mosquitoes inspired Needles

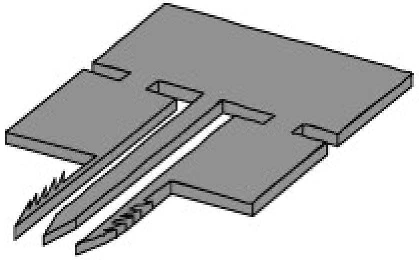






TECHNOLOGY:
Japanese microengineers created a **minute needle** just **1mm long** and with a diameter of **0.1 mm**. They etched slices of **silicon dioxide into a jagged shape** and bonded them together. There are two serrated shanks that form the outer surface of the needle. A **central shaft then slides between them to inject** or withdraw the sample. The needle is connected to a **small reservoir** that is equipped with an optical sensor to analyze samples.





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https://asknature.org/idea/mosquito-inspired-icroneedle/#.WEaGDLLNxQI

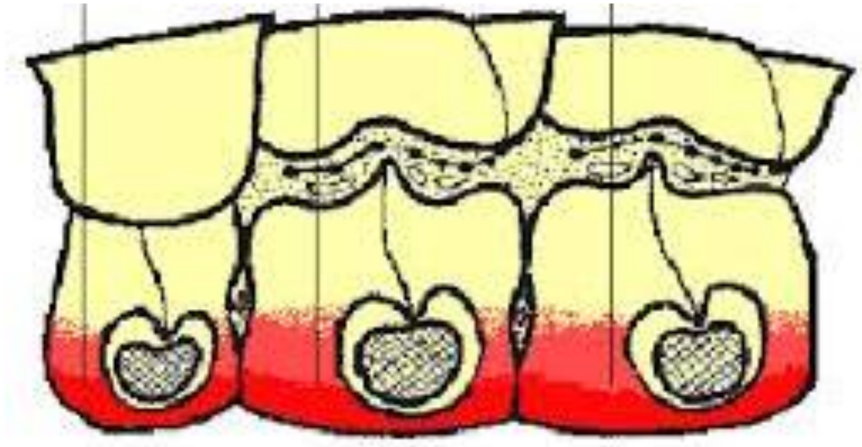
Thorax

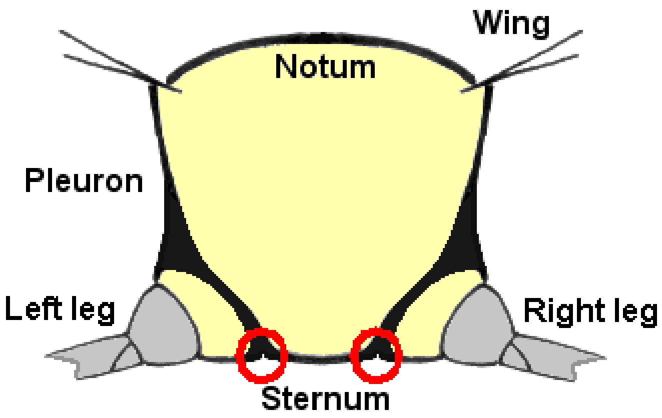
The insect thorax has three segments:

1. Prothorax.
2. Mesothorax.
3. Metathorax.

Each segment is delineated by an intersegmental suture. Each segment has four basic regions:

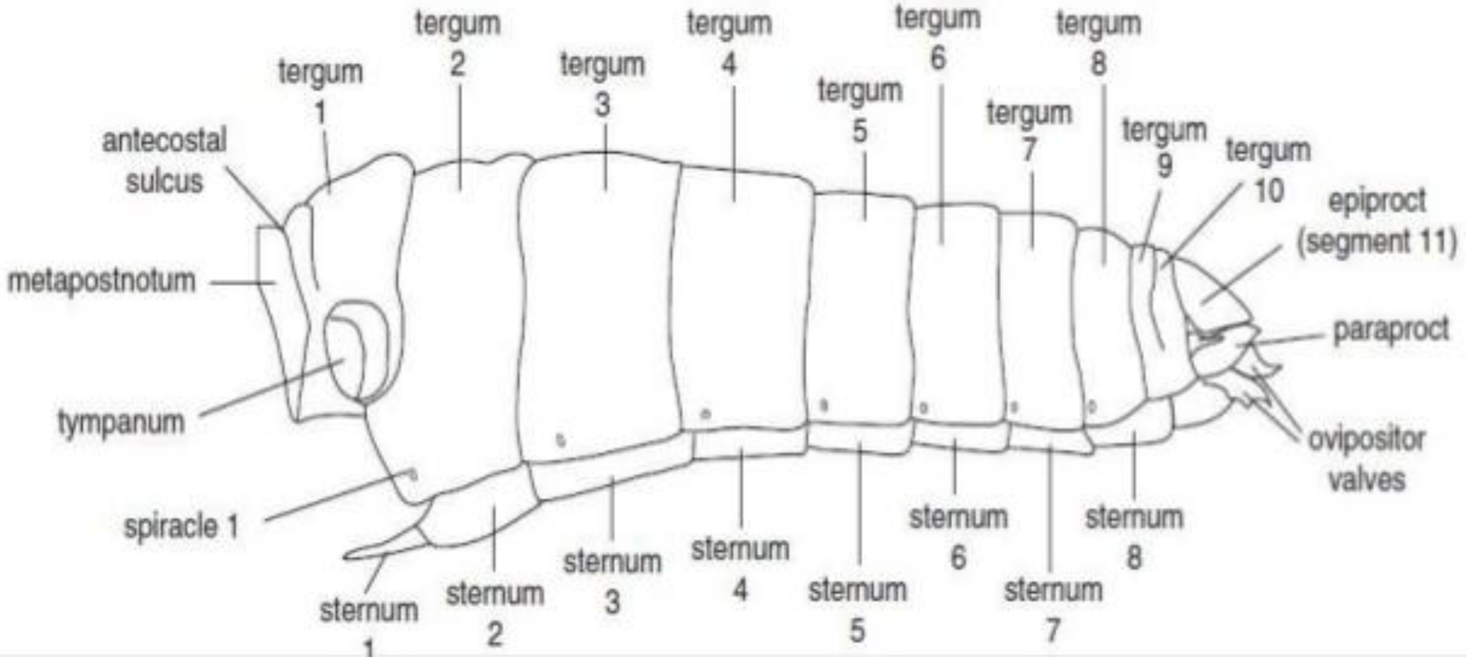
- Tergum (or notum), to distinguish it from the abdominal terga).
- Two lateral pleura (singular: pleuron).
- Sternum.



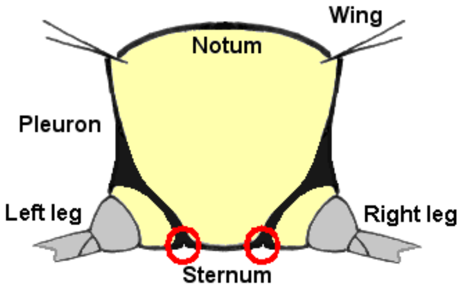


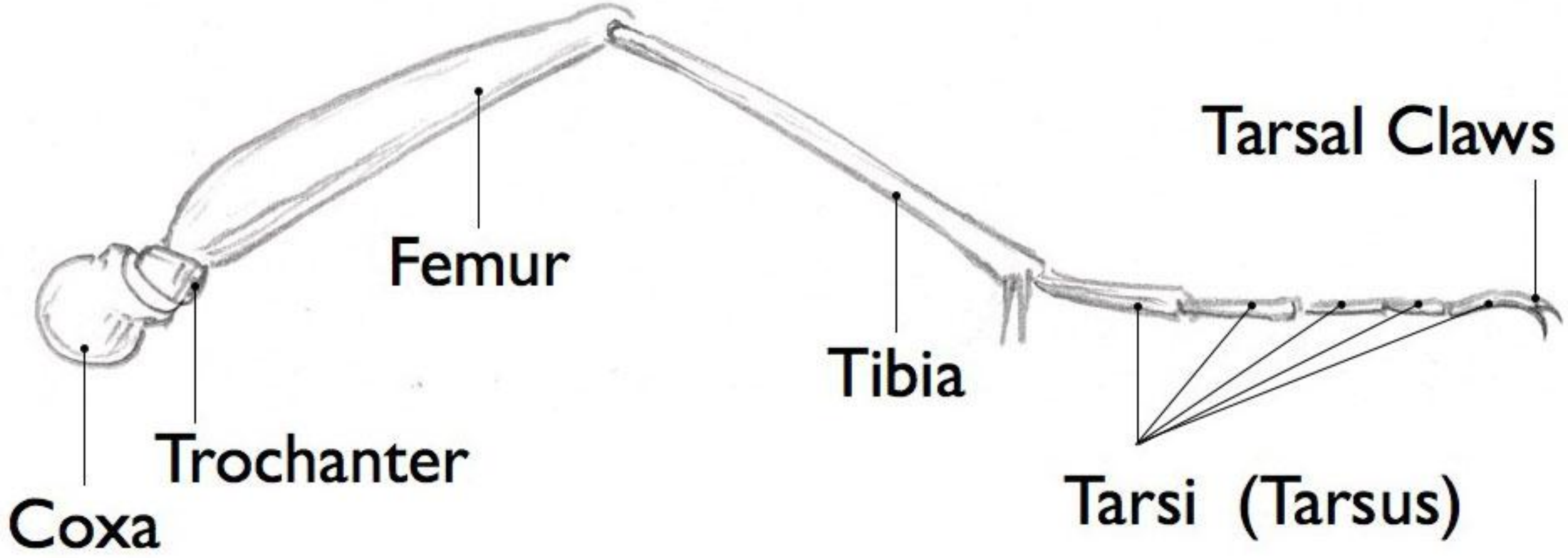
Abdomen

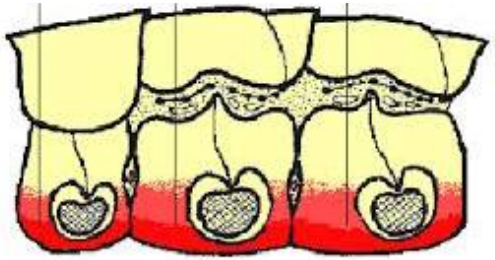
consists of 11–12 segments and is less sclerotized than the head or thorax.



Legs

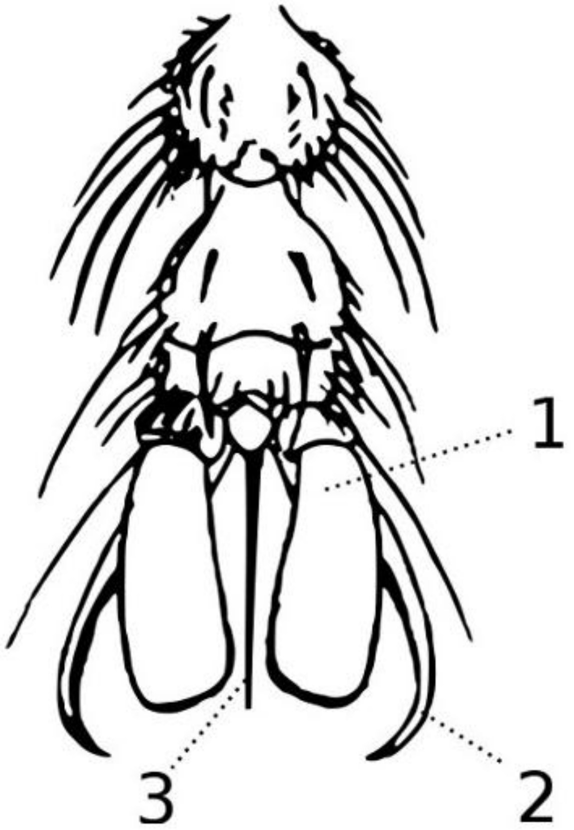

Wing
Notum
Pleuron
Left leg
Right leg
Sternum


Tarsal Claws
Femur
Tibia
Trochanter
Coxa
Tarsi (Tarsus)



Legs

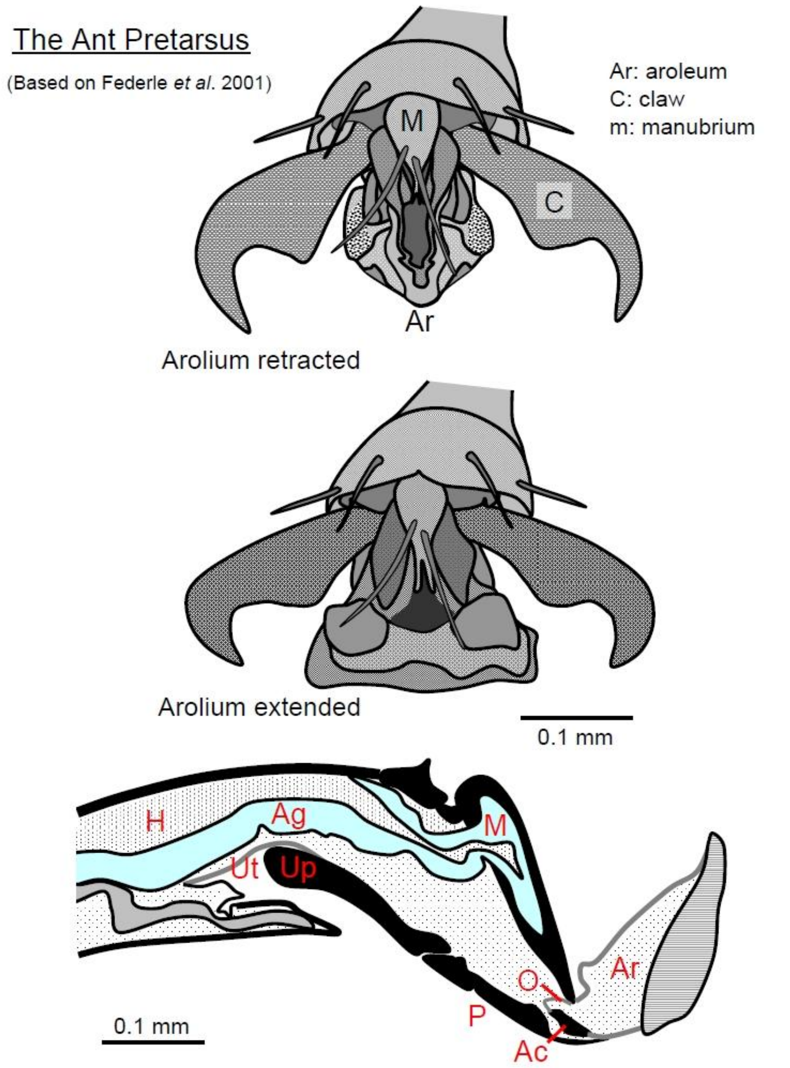
Pulvilli are lobes or padds that are located between the tarsal claws of many insects. The pads have adhesive properties, including the use of an adhesive fluid, and this helps the insect stick to the surface on which it is standing.



Legend

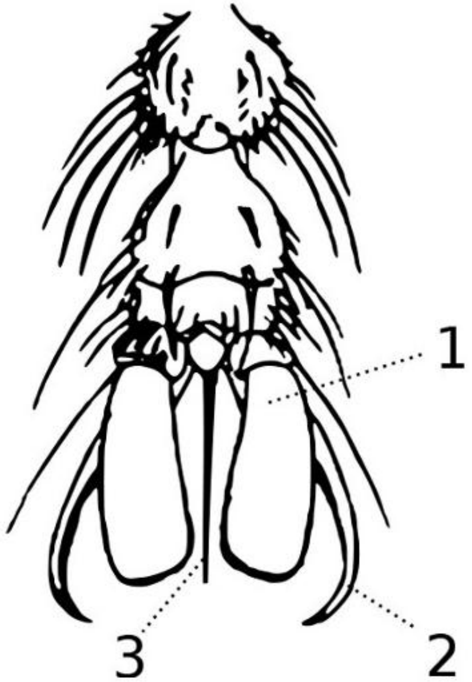
1. Pulvilli
2. Claw
3. Empodium

Legs



Above: longitudinal section through pretarsus. Ac: arcus sclerite, Ag: arolium gland, Ar: arolium, H: haemocoel, M: manubrium, O: opening, P: planta, Up: unguitractor plate; Ut: unguitractor tendon

Many insects possess a lobe or spine between the two claws at the end of the tarsus (the final segment in the leg of the insect). This lobe or spine is called an **empodium**.

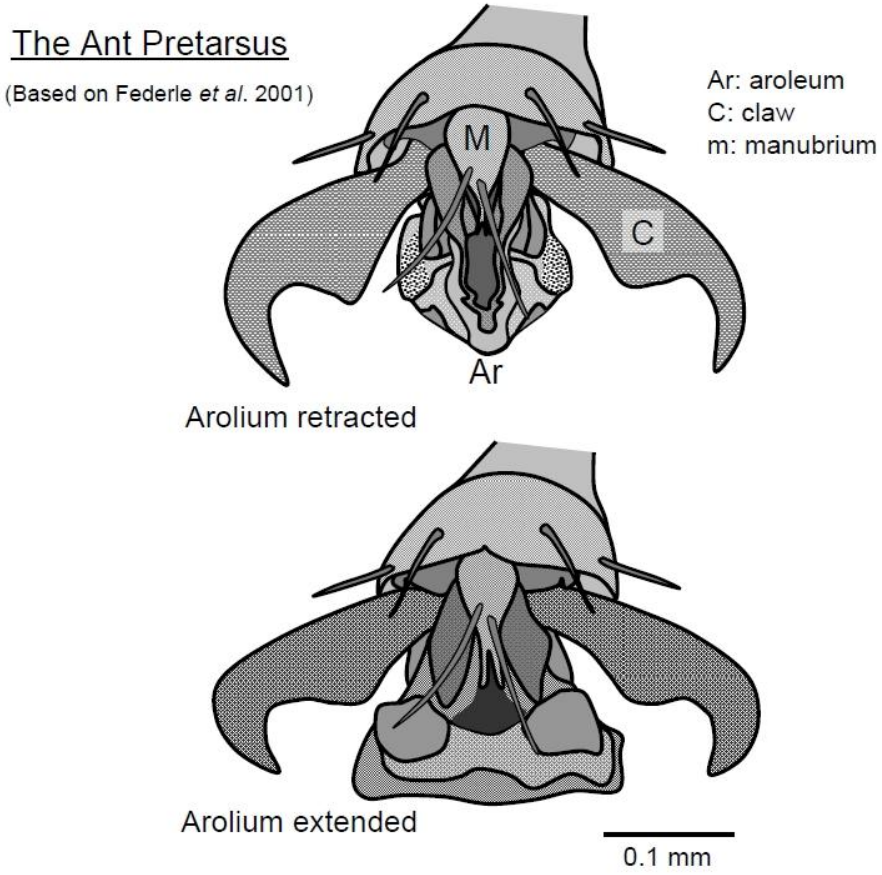


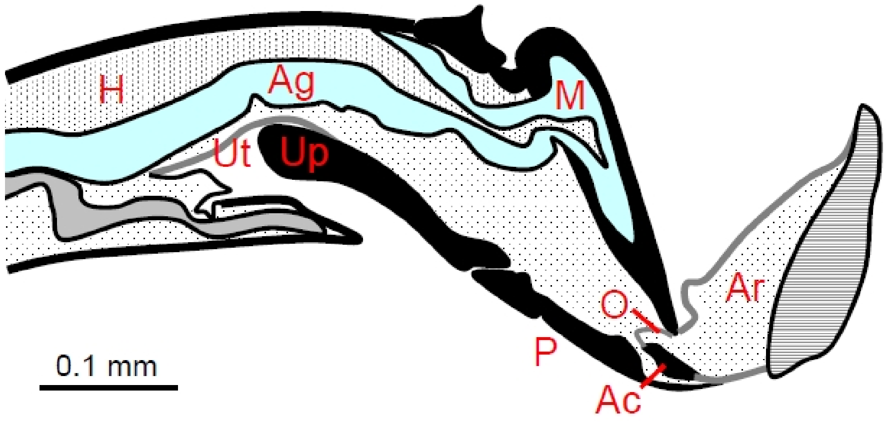
Legend

1. Pulvilli
2. Claw
3. Empodium

Legs

Above the unguitractor plate the pretarsus expands forward into a median lobe, the **arolium**. The arolium, and pulvilli are adhesive organs enabling their possessors to climb smooth or steep surfaces.





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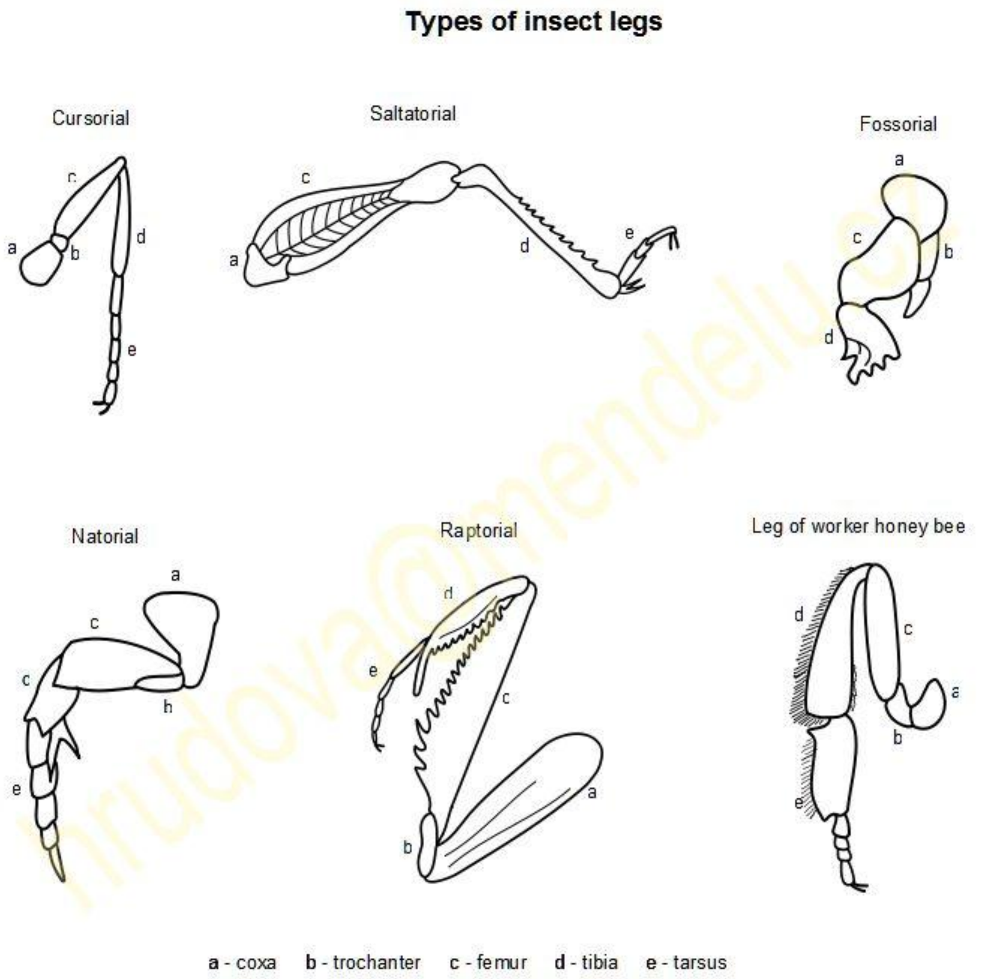
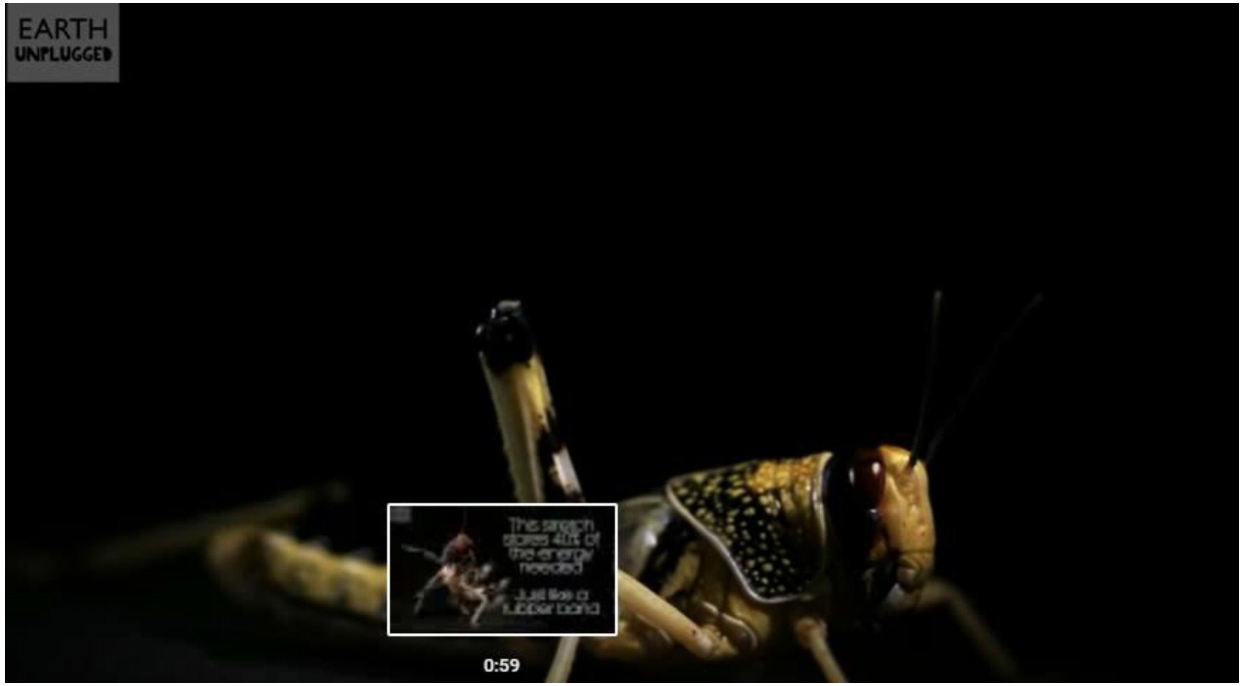
Legs

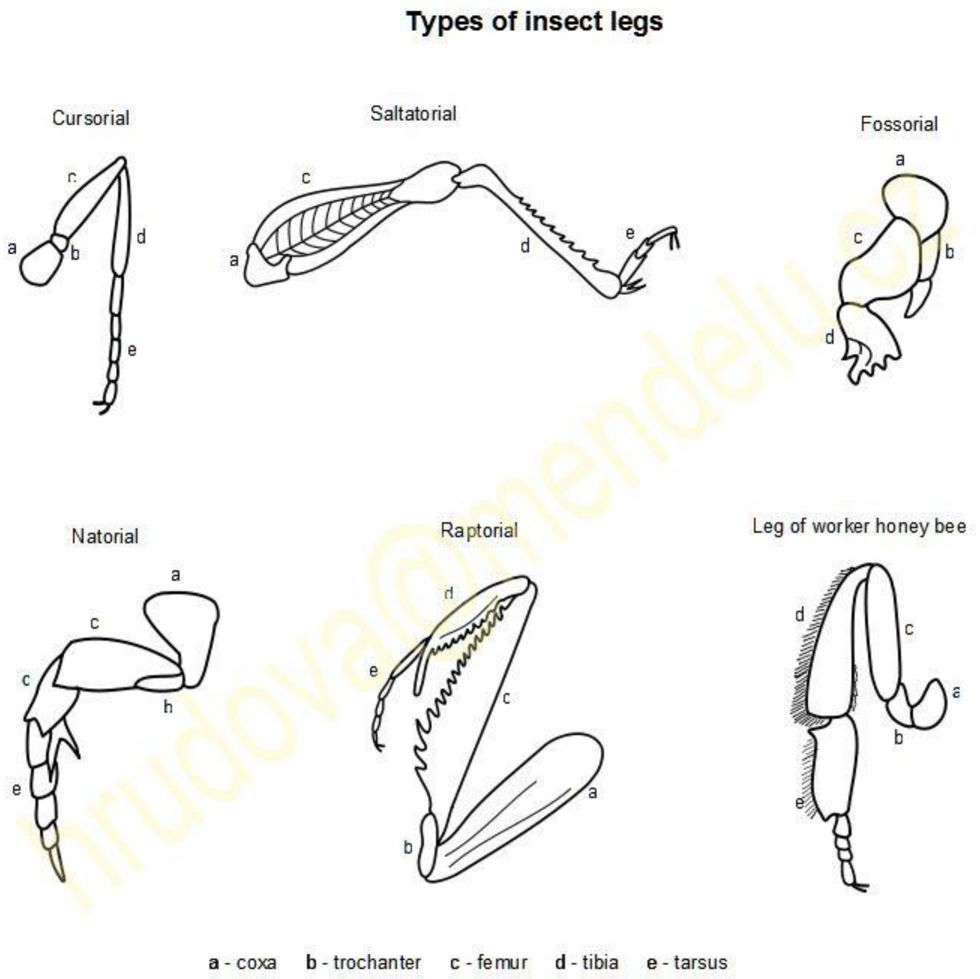
Various modifications for various of functions



Legs

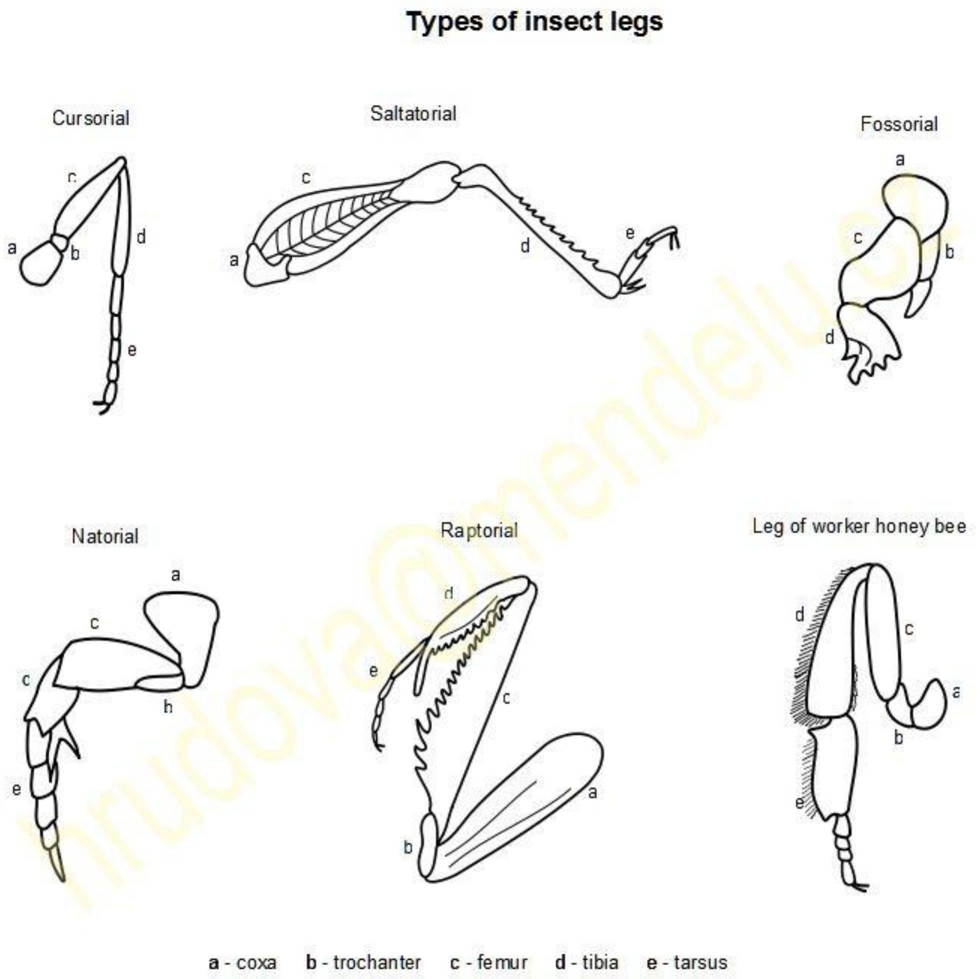
Various modifications for various of functions





Legs

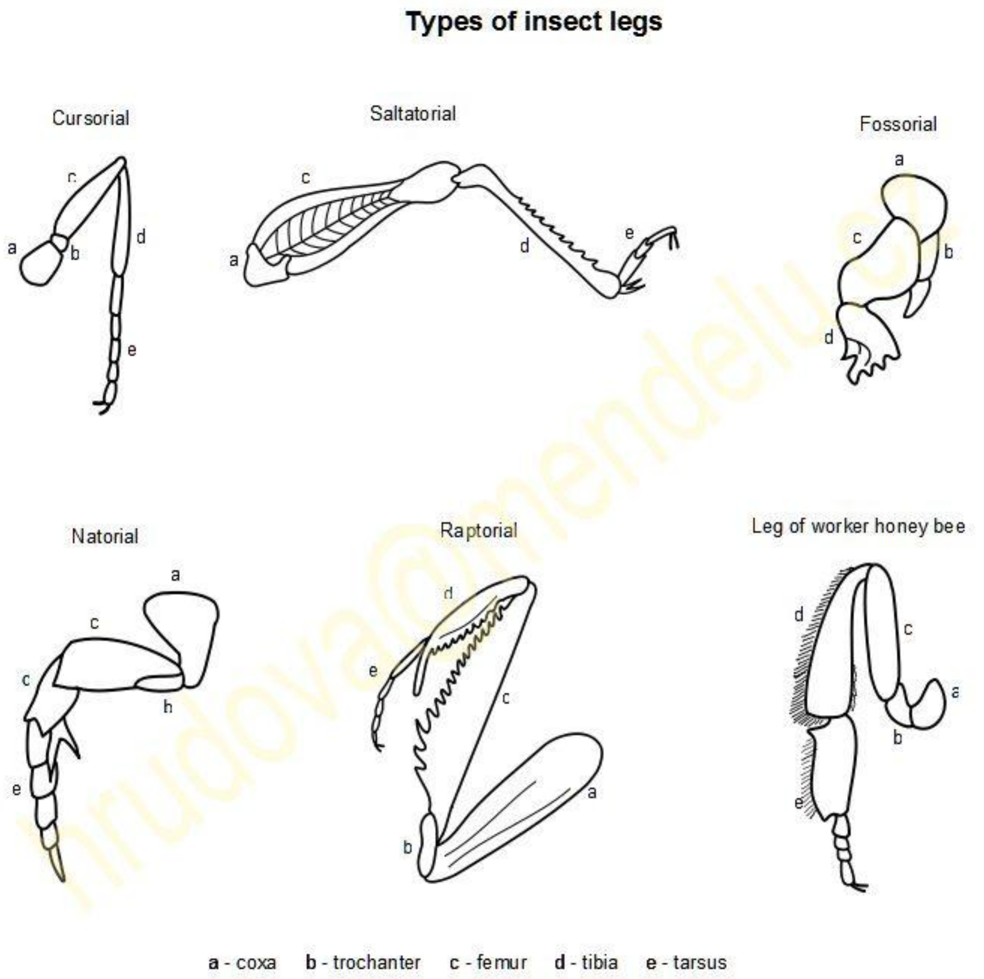
Various modifications for various of functions



Legs

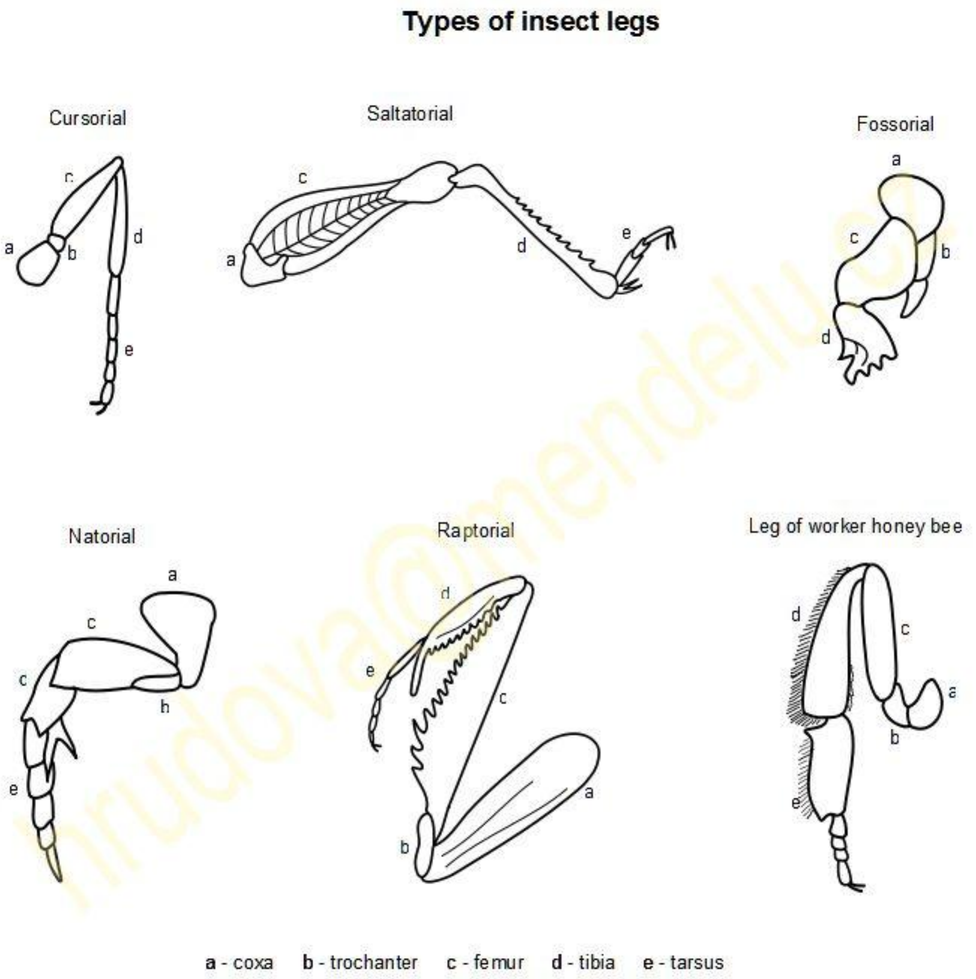
Various modifications for various of functions

Trichocorixa sexcincta



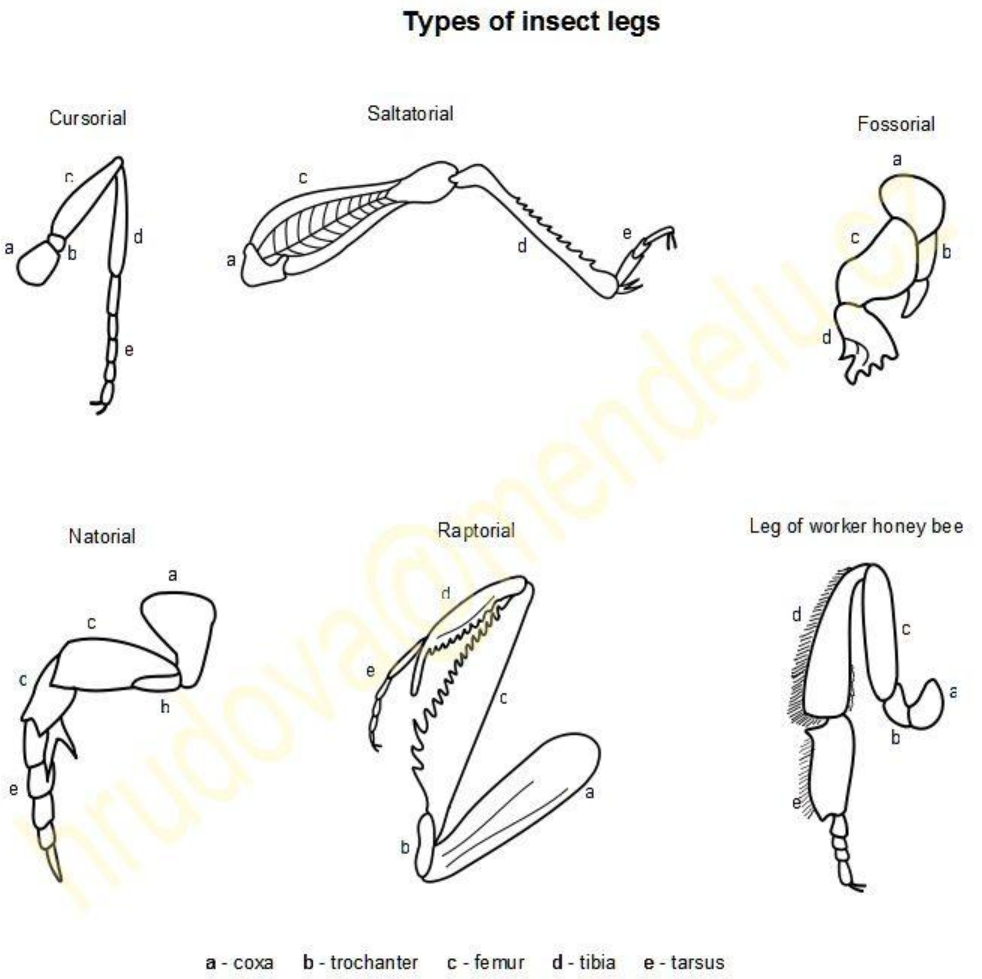
Legs

Various modifications for various of functions



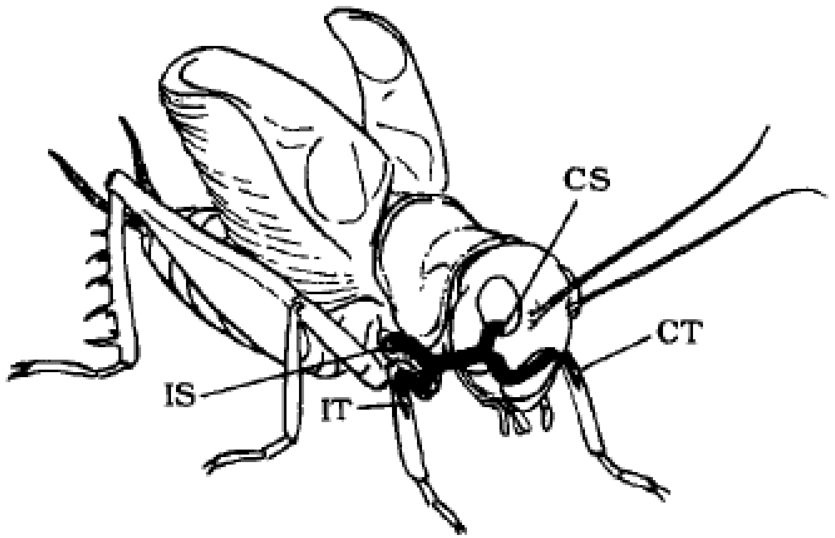
Legs

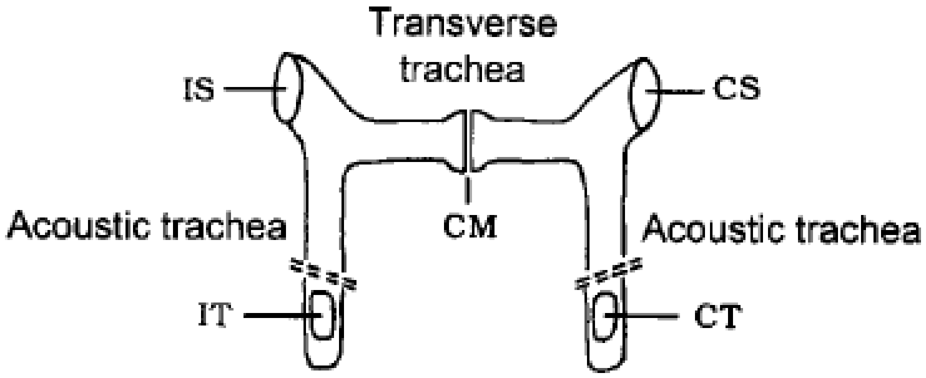
Various modifications for various of functions



Auditory legs

The cricket ear is located in the front legs and is a sound receiver with four acoustic inputs. In the case of the right ear, one input is the external surface of the eardrum (IT: ipsilateral tympanum). Sound also propagates through the acoustic trachea from the ipsilateral spiracle (IS) to the inner surface of the eardrum. Finally, sound from the contralateral spiracle (CS) and contralateral ear (CT) may reach the inner surface of the eardrum by propagating through the transverse trachea and the acoustic trachea. Note that the sound from the contralateral inputs has to pass a (double) central membrane (CM) in the transverse trachea.

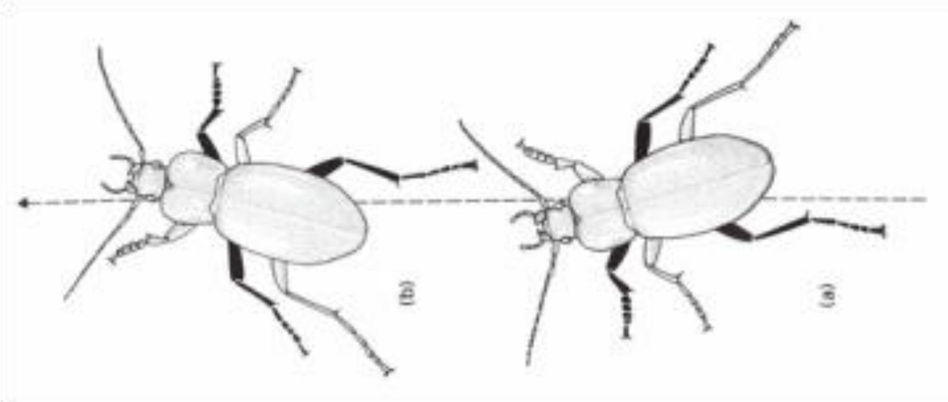


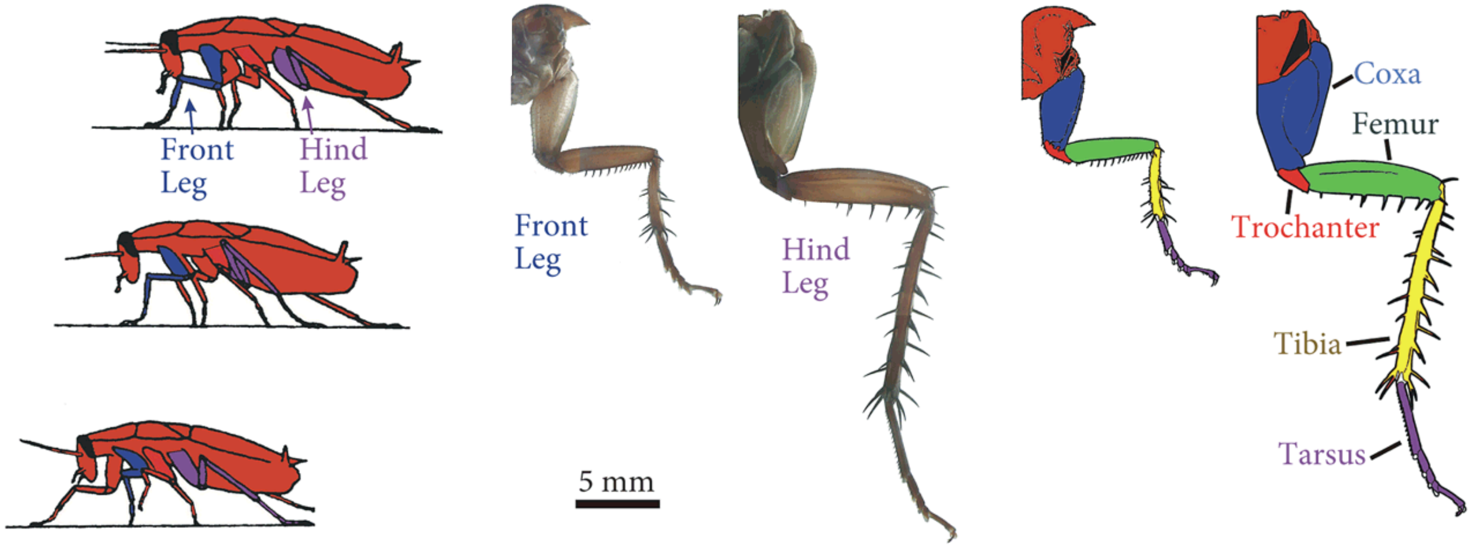


Michelsen, A., Popov, A. V., & Lewis, B. (1994). Physics of directional hearing in the cricket Gryllus bimaculatus. Journal of Comparative Physiology A, 175(2), 153-164.

Terrestrial legged locomotion

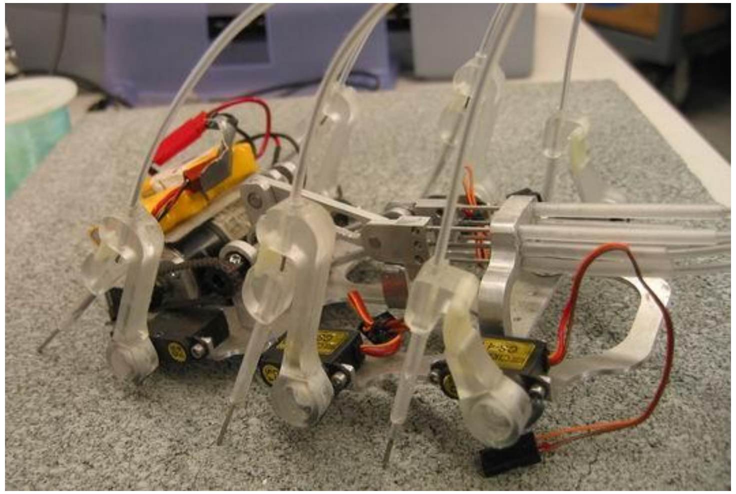
- Most insects have three pairs of legs positioned laterally in a wide stance.
- The body’s center of mass is low and well within the perimeter of support for optimal stability.
- Each leg serves both as a strut to support the body's weight and as a lever to facilitate movement.

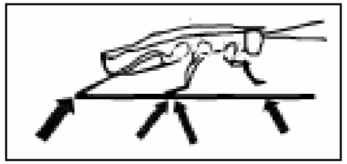


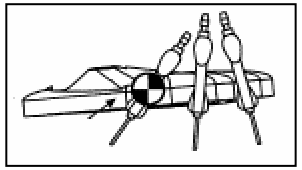


Terrestrial legged locomotion

RELIABILITY and ROBUSTNESS thanks to suspension systems and compliant legs. Intrinsic mechanical stabilization systems, called PREFLEXES [1], are exploited to minimize control complexity for locomotion in unstructured environments [2]







[1] Full, TU, Mechanics of a rapid running insect: two, four and Six-legged locomotion, *J. Exp. Biol.*, 156, 215-231, (1991)
[2] J.G. Cham,J.K. Karpick,M.R.Cutkosky, Stride Period Adaptation for a Biomimetic Running Hexapod, The International Journal of Robotics Research, 32(2), 1-13, (2004)

Terrestrial legged locomotion

At very **slow walking** speeds an insect moves only one leg at a time, keeping the other five in contact with the ground.

At **intermediate speeds**, two legs may be lifted simultaneously, but to maintain balance, at least one leg of each body segment always remains stationary. This results in a wave-like pattern of leg movements known as the metachronal gait.

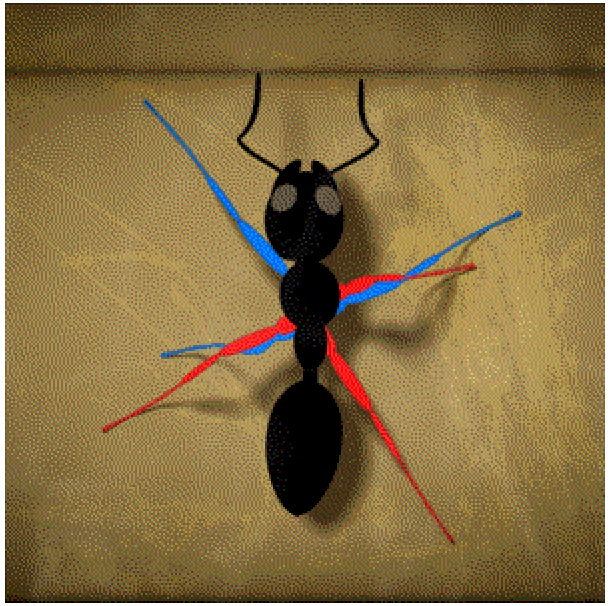
When **running**, an insect moves three legs simultaneously. This is the tripod gait, so called because the insect always has three legs in contact with the ground: front and hind legs on one side of the body and middle leg on the opposite side.

Terrestrial legged locomotion

Coordination of leg movements is regulated by networks of neurons that can produce rhythmic output without needing any external timing signals. Such networks are called **central pattern generators** (CPGs).

There is at least one CPG per leg.

Individual networks are linked together via interneurons and output from each CPG is modified as needed by sensory feedback from the legs.



Terrestrial legged locomotion

Festo BionicANTs