Swimming

I. Types of swimming

II. Methods for generating propulsion

III. Forces resisting movement

IV. Adaptations to different swimming modes

V. Relationships between swimming and ecology

Fishes swim in lots of different ways...

I. Types of swimming

- how much does the body flex?
  - A. **Anguilliform** (eel-like)
    - **body flexes one full wavelength or more**

  - B. **Carangiform** (jack-like)
    - **body flexes < 1/2 wavelength**
      - — fast
      - — *Thunniform* (extreme)

  - C. **Ostraciform** (boxfish-like)
    - **body rigid, tail oscillates**
      - — slow

These are extremes - there is complete gradation between the 3 types

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I. Types of swimming

- a more informative classification (Paul Webb) based on ...
  - — body parts used
  - — type of propulsive force generated

A. **B**ody and **C**audal **F**in swimming (**BCF**)
1. undulation
2. oscillation

B. **M**edian and **P**aired **F**in swimming (**MPF**)
1. undulation
2. oscillation
3. rowing/sculling

undulation: *wavelengths pass down length of body (or fin)*

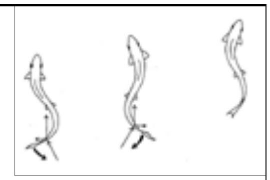
oscillation: *structure (fin) pivots on a base*

Keep in mind that a fish might need to do different things while swimming:
- cruise
- accelerate
- maneuver

II. Generating propulsion

A. BCF swimming

1. BCF undulation
   - most common
   - “fishy swimming”



- **a wave of muscular contraction from head to tail**
  - swings tail back and forth
  - strength & amplitude of contraction increase towards tail

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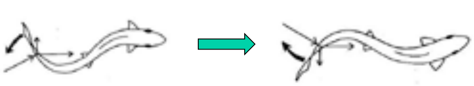
- part of fish pushing against water (side or tail) creates ***normal force*** (reactive) pushing in opposite direction

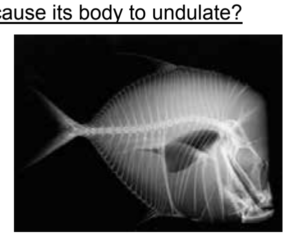
- since amplitude is greatest at tail, thrust is greatest there

- **normal force** has two components:
  - **thrust** pushes fish forward
  - other component pushes to side
    - — side to side component is cancelled out since body and tail move side to side



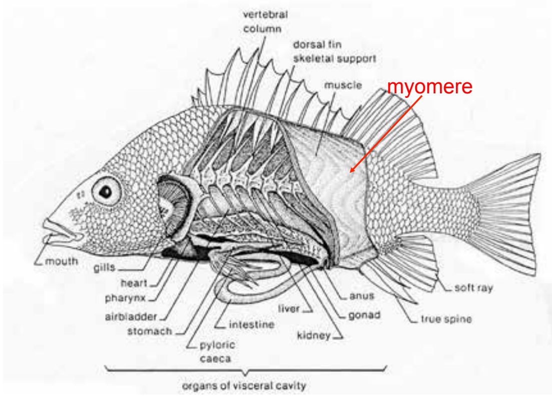
Biomechanics: how does the fish cause its body to undulate?

- **muscles** provide power
- **bones** act as levers
- **nerves** trigger muscles



1. **Bones**
   - head acts as fulcrum (heavy)
   - vertebral column is incompressible, but flexible

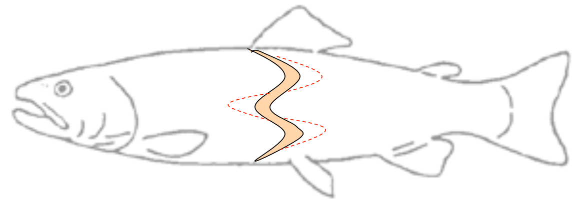
2. **Muscles**
   - divided into sections, myomeres (myotomes)



2. Muscles

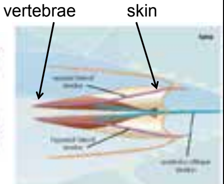
Form

- divided into sections, myomeres (myotomes)
- separated by connective tissue, myosepta, that connect to vertebrae
  - **myomeres shaped like sideways "W" - middle connects forward, sides to back**
  - **one myomere per vertebra**



Form

- myomeres are layered on top of each other and link vertebrae to skin and other distant vertebrae through tendons
- layers of myomeres looks like rings in cross section

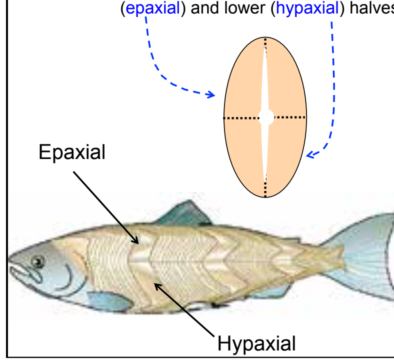


Tuna

Form

— muscle mass divided into 4 blocks:

- a septum divides muscle on one side from other
- another septum divides muscle on one side into upper (epaxial) and lower (hypaxial) halves



Function: make body undulate

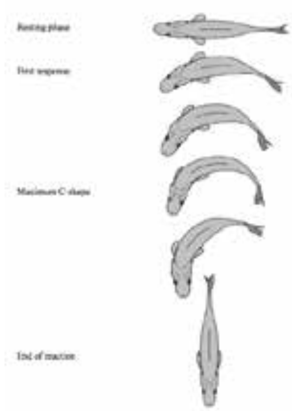
- paired myomeres are sequentially innervated by spinal nerves (one pair per vertebra)
- causes body to bend because myomeres on one side contract, while other member of pair on other side relaxes
- wave of contraction passes down length of body, increasing in amplitude

http://www.oeb.harvard.edu/lauder/videos.htm

Startle response

- *a special way to generate very rapid acceleration*
  - normal sequence of innervation of myomeres aborted
  - all myomeres on one side contract at once (then same on other side)
  - generates 2 big contractions
  - body bends into a "C" instead of "S"

➢ done by Mauthner cells, giant axons, that run length of body (not found in Chondrichthyes)



Two types of muscles:

- **red**
  - continuous, moderate paced swimming (e.g., tunas)
  - efficient, sustained aerobic metabolism
  - more blood, O_2, and energy stores (fat)

- **white**
  - bursts of fast swimming (e.g., flounders)

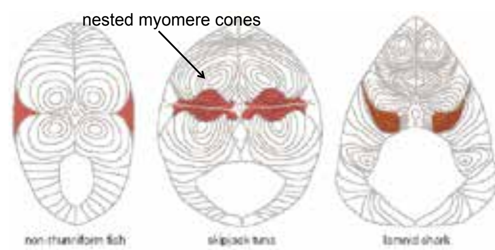
Differences between red and white muscle in fishes

attribute	red muscle	white muscle
shape of fiber	slender	stout
contraction	weaker, slower	stronger, faster
blood supply	abundant	sparse
O_2 binding pigment	myoglobin	none
mitochondria	abundant	sparse
fat content	high	low
O_2 consumption	high (6-7x)	low
mass	small	large

Can tell swimming behavior by amount of red muscle in flanks:

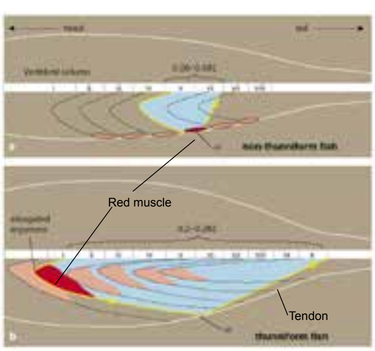
Behavioral group	% red muscle
bottom sitters	near 0
floater	7-10
continuous swimmers	11-20

Red muscle placement in tunas, lamnids, and other fish



- red muscle sits just under the skin in most fishes
- in tunas and lamnid sharks, continuous swimmers that retain body heat and metabolically function at higher than ambient temperatures, red muscle is buried deep
- tunas and sharks have elongated myomeres = more overlapping rings in cross section

Myomere length and red muscle placement is different in tunas than in other fishes



Non-Thunniform

- each myomere extends only 6-8% of body length
- red muscle under surface of skin
- tendons connect myomeres to adjacent vertebra (e.g. vertebra 5 connects to 6)

Thunniform

- each myomere extends 20-25% of body length
- red muscle internal
- long tendons project muscle force from each vertebrae to the tail (e.g. vertebra 1 connects to 10)

Continuous swimmers with lots of red muscle often use a different mechanism to generate propulsion…

BCF oscillation

- propulsion generated by **lift**
- tunas and mackerels

BCF oscillation
- narrow caudal peduncle and lunate tail ("wing on a stick")
- fins have high aspect ratio (measure of lift per unit area)

Aspect ratio = S^2/A

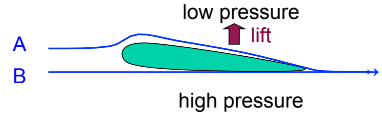
where S = length of fin
A = surface area of fin

- high aspect ratio reduces drag, too

- myosepta specialized into tendons
  - allows rapid beating of tail (up to 10 beats/second)

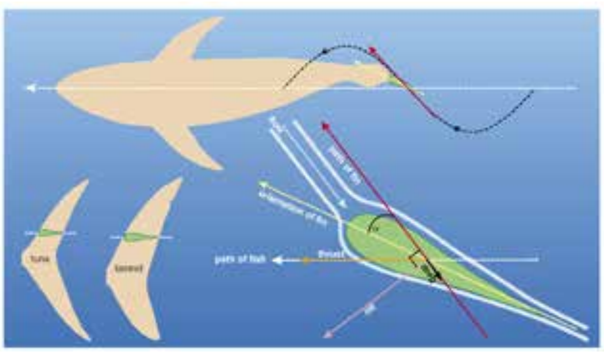
BCF oscillation
- how lift is generated for propulsion:

– tail moved from side to side to positions with positive angles of attack



- particle A has to go farther -- therefore A must go faster
- causes lower pressure on A's side of fin
- generates lift towards A's side

Longer distance along front edge ⇒ faster water velocity
⇒ less pressure ⇒ lift in horizontal direction



http://www.arkive.org/yellowfin-tuna/thunnus-albacares/video-00.html

II. Generating propulsion
A. BCF swimming

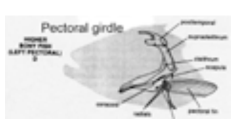
B. MPF swimming
1. Rowing (sculling)
2. Oscillation
3. Undulation

http://video.google.com/videoplay?docid=312259830463034721

MPF swimming:

1. **Rowing** (sculling)
   - same as oars...
     — power stroke with fin expanded
     — return stroke with fin collapsed

requires:
- **strong, complex pectoral girdle**
- **good nervous control**
- **large muscles for those who swim lots (wrasses, parrotfish)**



http://www.youtube.com/watch?v=KVVXGtNN35E

MPF swimming:

1. Rowing (sculling)
2. **Oscillation**
   - pectoral fins oscillated slowly or rapidly (like a bird)
   - generates lift

- requires large muscle mass in pectoral girdle

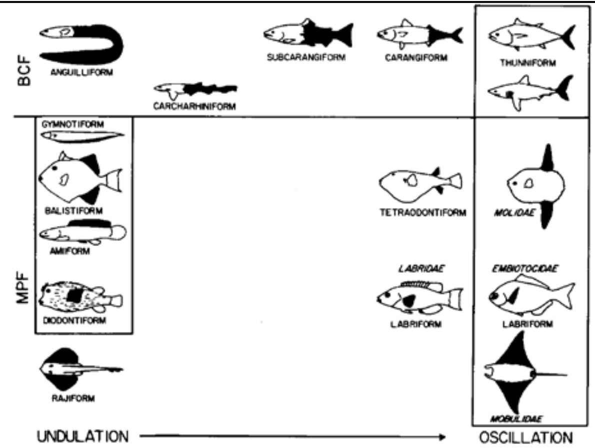
http://www.youtube.com/watch?v=QOthel4LTmQ

MPF swimming:

1. Rowing (sculling)
2. Oscillation
3. **Undulation**

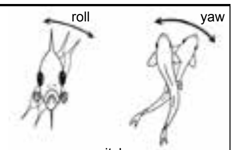

- usually median fins (dorsal, anal)
- sinusoidal waves run down fins
- can also undulate pectoral fins (skates, puffers)

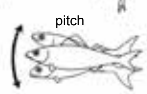

http://www.youtube.com/watch?v=geajxS37mgg



Median & paired fins are also used to:

- stabilize
- maneuver





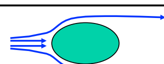
- **caudal fin**: rudder
- **dorsal & anal**: prevent roll
- **pectorals**: control yaw (side to side)
  used to brake
  sometimes used to generate lift
- **pelvics**: control pitch (up/down orientation) by generating lift

  - evolutionary trend for pectorals and pelvics to move closer to center of gravity
  - **allows for precise maneuvering**

III. Forces resisting movement:

- **inertia**
  - energy to start body in motion
- **drag**
  - force that pushes back against direction of motion
  - particularly important to fish because…
    - **water is 800x more dense than air**
    - **water is "sticky" (viscous)**
  - three components:
    1. form drag
    2. friction drag
    3. pressure drag

Drag:



Form drag: caused by displacement of water

- proportional to:

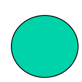
  (cross-sectional area of body) x (velocity^2)

- minimize by being slender

Drag:

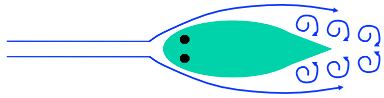
Friction drag: caused by water molecules sticking to skin

- proportional to: (surface area of body) x (velocity)
- minimize surface area (be a sphere)



Drag:

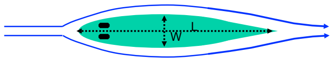
Pressure drag: caused by pressure differential between front and back of fish (ultimately caused by turbulent vortices)



• minimize by...

-- improving streamlining (fusiform shape, fin slots)

-- directing flow (caudal keels, finlets, scales)



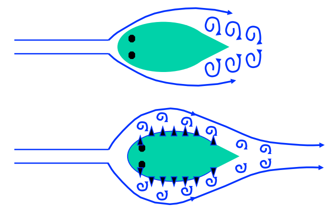
L/W > 4-5 for laminar flow

Flow direction by vortex generators

- small vortices can prevent larger ones
  - **placoid and ctenoid scales may have evolved independently in sharks and teleosts**
  - **possibly because they retard separation of the boundary layer**

smooth skin

rough skin



IV. Adaptations to different modes of swimming

- tradeoffs

compare 3 extremes:

- **cruisers**
- **accelerators**
- **maneuvers**

Cruisers (tunas, mackerels, marlins, jacks, lamnid sharks)

- always cruising… don't need to overcome inertia
- maneuvering relatively unimportant
  - **minimize drag**
  - **maximize efficiency**

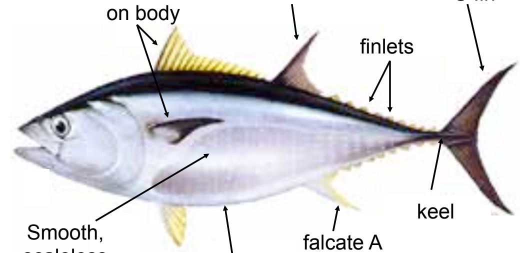
Cruisers

(tunas, mackerels, marlins, jacks)

minimize drag:

- form drag:
  - **- streamline**
  - **- minimize body motion**
- friction drag:
  - **- smooth surface: small or no scales**
  - **- lunate tail reduces "wetted surface area"**
- pressure drag:
  - **- slender caudal peduncle**
  - **- flow fences: caudal keels**
  - **- pointed fins**
  - **- microturbulence: finlets and scales**

Disadvantages:
1. poor quick start
2. poor turning
3. poor hovering



Cruisers

- **maximize efficiency**

endothermy - muscles are more efficient at higher temperatures (3x more power for every 5˚ C)

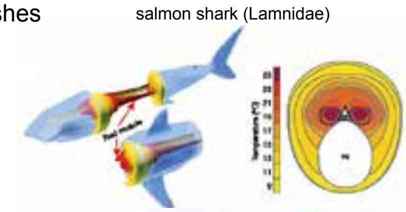
- **some fish (bluefin tuna) can maintain muscles at up to 14˚ C warmer than water**

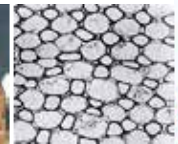
achieved by:

- **having red muscle close to body core**
- **using countercurrent heat exchangers**

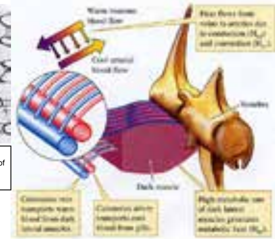
Endothermy in fishes

salmon shark (Lamnidae)





Microscopic view of cross section through countercurrent heat exchanger of a tuna. Arteries have thicker walls and veins thinner walls



Accelerators

(barracuda, pike, giant sea bass, groupers)

- typically ambush prey
- need to overcome inertia, drag less important

- **generate thrust by BCF undulation**
- **maximize thrust by having large surface area in rear of body**
- **lots of white muscle, little red, high overall muscle mass**

Maneuvers

(butterflyfishes, damselfishes, angelfishes)

- slow moving, so drag & inertia relatively unimportant
- deep, compressed bodies that can be turned quickly

- **MPF rowing/sculling**
- **paired fins placed around center of gravity**

V. Relationship between swimming and feeding ecology

Webb's hypothesis: swimming specializations can be explained by distribution of food

1. Food patchy (& widely dispersed) ⇒ **cruiser**
2. Food uniformly abundant
   a. **evasive prey ⇒ accelerators**
   b. **non-evasive prey ⇒ maneuvers**

Two criticisms of this hypothesis:

1. Isn't avoiding predators more important than feeding?
2. Isn't mouth structure more important for feeding success than swimming mode? (Karl Leim)