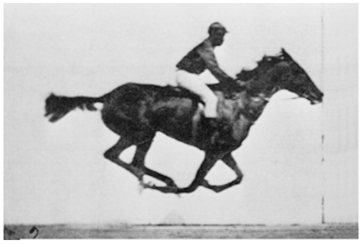
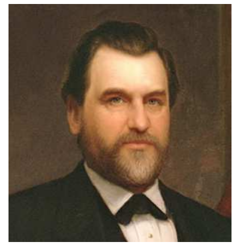
Animal Locomotion



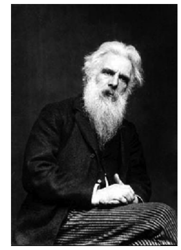
Feb 8th, 2007

Photographic study of locomotion began with a bet (1872)



Leland Stanford

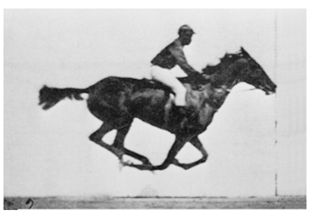
"unsupported transit"



Eadweard Muybridge

Commissioned to establish whether a galloping horse ever has all four feet off the ground simultaneously with new photographic technology

Edweard Muybridge, 1887 using a series of 50 electrically triggered still cameras at 0.022sec interval (45fps)



zoopraxiscope

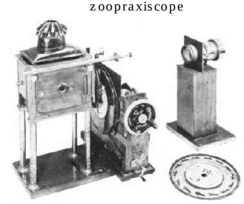
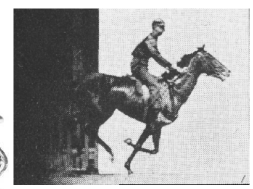
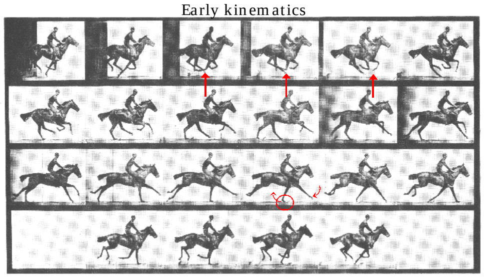


Photo 1.2: Muybridge's Zoopraxiscope. (Courtesy of Kingston-upon-Thames Museum and Art Gallery, Stanford University of Art.)

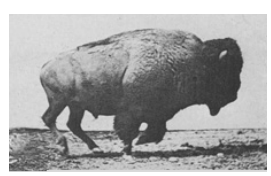


Early kinematics

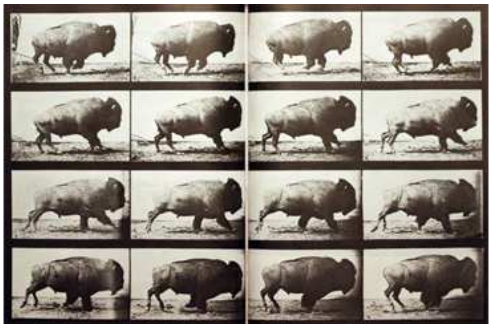


Edweard Muybridge, 1887 using a series of electrically triggered still cameras at 0.022sec int

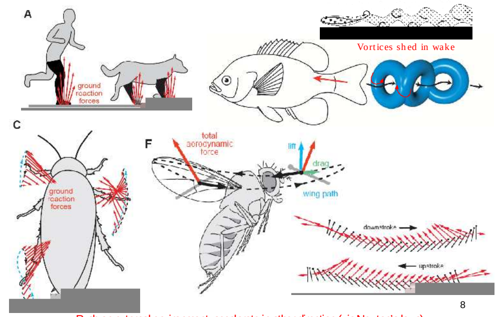
Running Buffalo



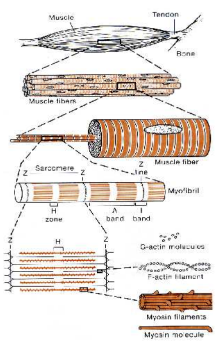
Buffalo



How do animals move?

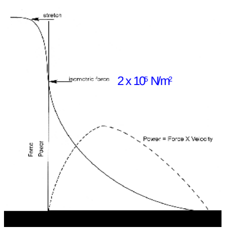


Push on external environment, accelerate in other direction (*via* Newton's laws)

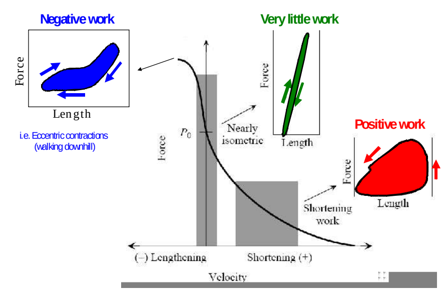


Muscle Properties

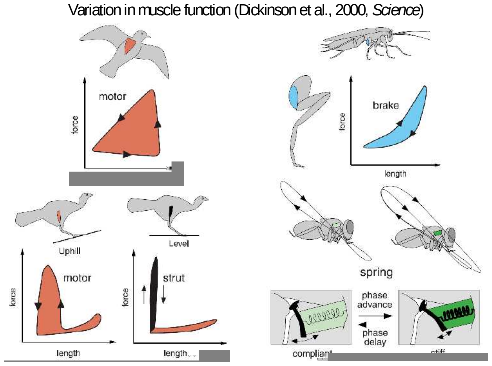
1. Force ∝ Area
2. Shortening Velocity is inversely related to Force
3. Force- Velocity (Hill Relation) is experimentally derived.



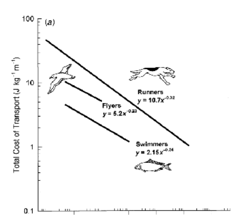
Force–length behavior of a muscle (work loop)



Variation in muscle function (Dickinson et al., 2000, *Science*)



Moving in Air vs. Water

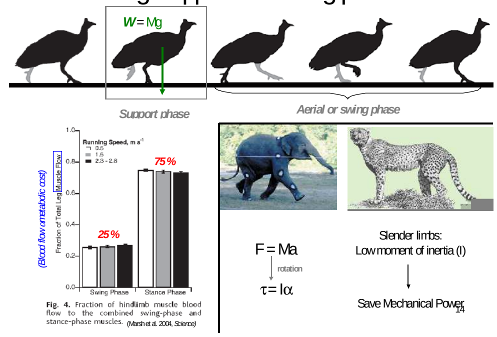


$F_{drag} = ½C_D S\rho U^2$

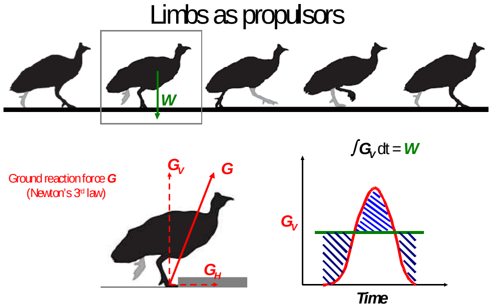
$F_{Lift} = ½C_D S\rho U^2$

Wheels in nature: why so few?

Running: support and swing phases

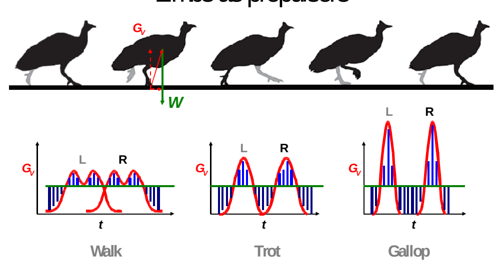


Limbs as propulsors



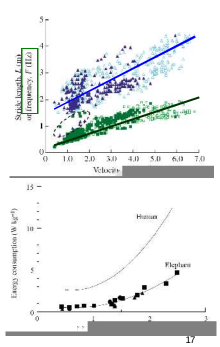
Over a series of strides the average vertical force must equal the animals weight

Limbs as propulsors



If $U\uparrow$ by $f\uparrow$ then $G_v\uparrow \Delta t\downarrow, P_{mech}\uparrow$

How to run faster & its metabolic cost



Hutchinson et al. 2006;
Langman et al., 1995, *J. Exp. Biol.*

Cost of transport (*mammals*)

(White & Seymour, 2003, 2005 *PNAS, JEB*)

$\Delta E = F_r \Delta x$ (Energy expended; Resistive force; Distance)

$F_r = \Delta E/\Delta x$

$F_r = E_m$ (Energy per meter of travel [J/M])

$E_{tr} = F_r/M = E_m/M$ (Cost of transport; Energy per meter of travel [J/kg·M])

$E_{tr} = F_r/M = E_m/M$

$P = F_r \cdot U = \eta\Gamma = bM^{2/3}$

$F_r = \eta\Gamma/U$

/M

$F_r/M = \eta\Gamma/UM$

$E_{tr} = F_r/M = \eta\Gamma/UM$

$E_{tr} = \eta bM^{2/3}/UM$

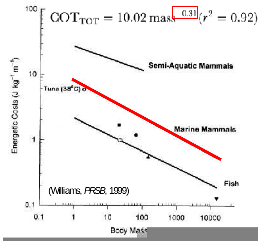
$E_{tr} = cM^{-1/3}/U$

Cost of transport (for marine mammals)

$E_{tr} = cM^{1/3}/U$

Speed is invariant of M (50kg → 50tons) for marine mammals: empirically derived (Sato et al. *PRSB*, 2006)

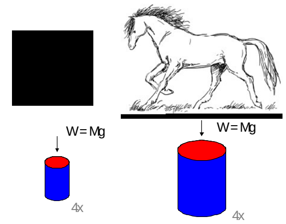
$E_{tr} \propto M^{1/3}$



Limbs (bones & muscles) bearing weight: scaling

Body mass $\propto L^3$

Bone X.S. area $\propto L^2$



Bigger bodies have limbs that experience more stress (F/A)

Bone strength $\propto L^2$ Muscle strength $\propto L^2$

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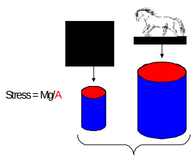
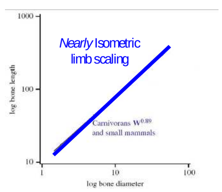
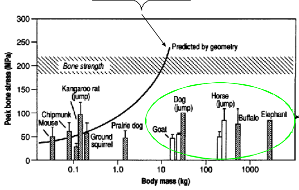
Limbs bearing weight







Why don't these animals experience stresses that break bones?

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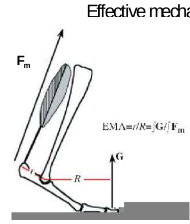
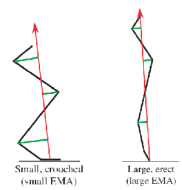
Effective mechanical advantage (EMA)





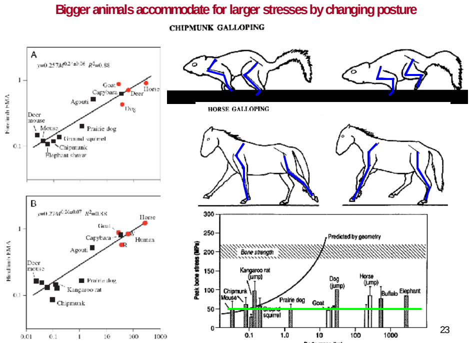
Moments (cross-product of force vectors and moment arms) around joint must be balanced: external moments produced by the ground force are counteracted by muscle moments.

$F_m \times r = G \times R$ $EMA = r/R = G/F_m$

With a straighter limb posture, lower joint moments and muscle forces are required to exert the same ground contact force 22

(Biewener 2005, JEB)

Bigger animals accommodate for larger stresses by changing posture



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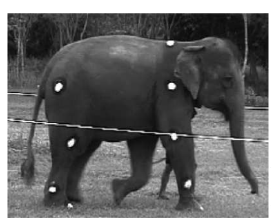
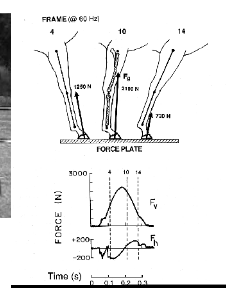
(Biewener 1989, Science)

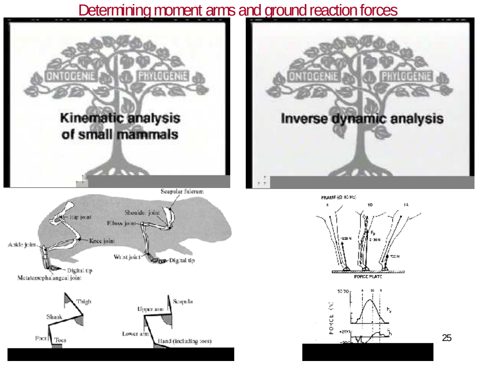
How to measure EMA





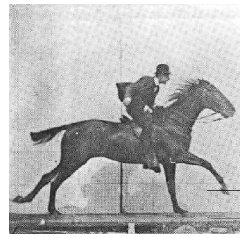
$EMA = r/R = G/F_m$

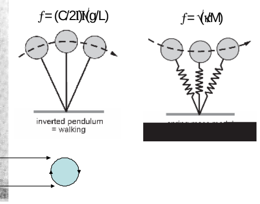
Determining moment arms and ground reaction forces



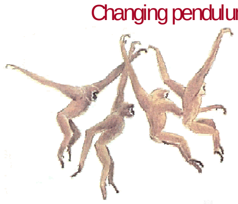
Periodic motion & Resonance

Store mech E in elastic oscillations, via elastic structures, and recover that E *only* if the timing is right: resonant frequency *f*

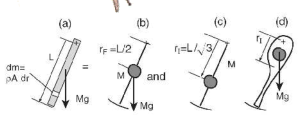




Changing pendulums for speed



$f \propto \sqrt{(g/L)}$



Leg tuned for higher frequency with mass centered close to the hip.

B.K. Ahlborn et al. / Zoology 109 (2006) 43–53

Periodic motion & Resonance

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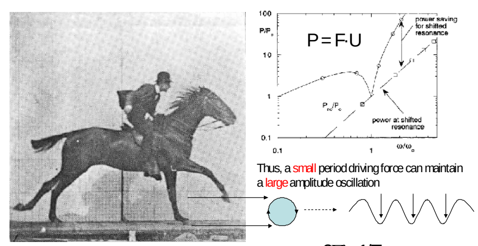


Thus, a small period driving force can maintain a large amplitude oscillation

$\omega = 2\pi f = 1/T$

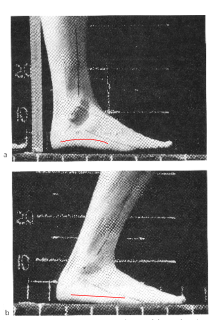


FIG. 6.7 A foot resting lightly on the ground (a), and at the stage of a running stride at which the peak force acts (b).

Tendons and ligaments act as springs

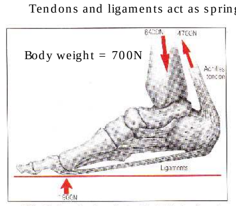
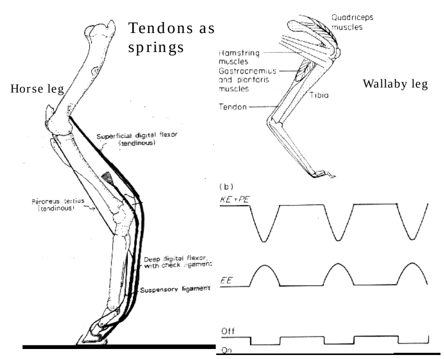


FIG. 6.8 Skeleton of a foot, showing the Achilles tendon and the ligaments of the arch. The arrows represent the peak forces in a running stride.



Periodic motion & Resonance

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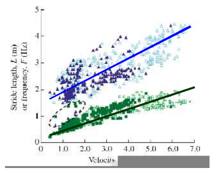
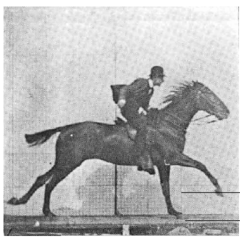
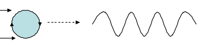


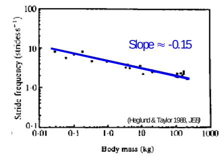


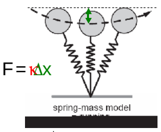
$f = \sqrt{(\kappa/M)}$



$\omega = 2\pi f = 1/T$

Running like a spring: elastic energy storage

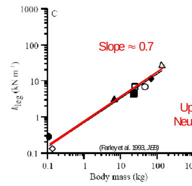




$F = \kappa\Delta x$

$f = \sqrt{(\kappa/M)}$

Resonant frequency — Spring constant — Mass



Stiffness from:
Upright posture (EMA)
Neural control of muscles

$f^2 = (\kappa/M)$

$Mf^2 = \kappa$

$M(M^{-.14})^2 = \kappa$

$M^{.7} = \kappa$

Saving energy (30-70%) with resonance: jellyfish bells modeled as a harmonically forced, damped oscillator (Demont & Gosline, 1988)

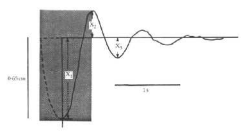
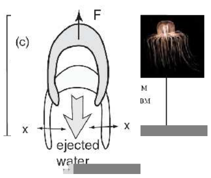


Fig. 1. A typical free vibration of the inside diameter of the bell of the hydromedusan *Polyorchis*. The maximum amplitude of oscillation is 6·45 mm.



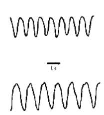
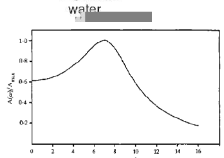
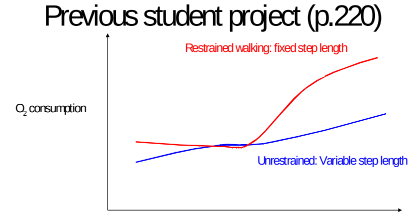
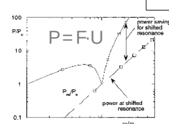


Fig. 3. Typical records of the inside diameter of the bell of a jellyfish contracting in continuous trains.



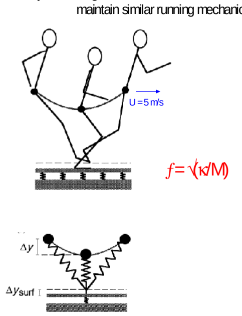
Previous student project (p.220)



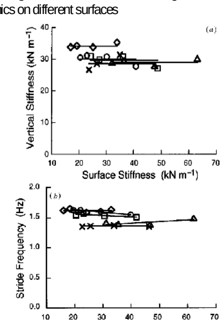


Speed

Runners adjust their leg stiffness to accommodate changes in surface stiffness, allowing them to maintain similar running mechanics on different surfaces



$f = \sqrt{(\kappa/M)}$



Basilisk lizard running on water

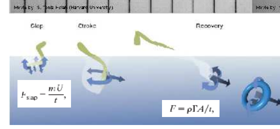


Table 1. Summary of single-leg peak reaction forces produced during a step

Direction	Slap, % (*n*)	Stroke, % (*n*)
Vertical	113 ± 8 (5)	39 ± 6 (3)
Fore–aft	63 ± 8 (5)	47 ± 14 (4)
Transverse	79 ± 17 (3)	37 ± 13 (3)

Positive reaction forces point up, forward, and medial to the foot being analyzed. Results are presented as mean percent of body weight ± SEM, followed by the number of individuals analyzed in parentheses. Twenty-four total sequences were analyzed (two to six sequences per individual).

Highlights for next week

Tuesday: Dan Dudek

Thursday: John Gosline