Walking

Modeling of
Human Movement

MCEN 4228/5228

Fall 2021

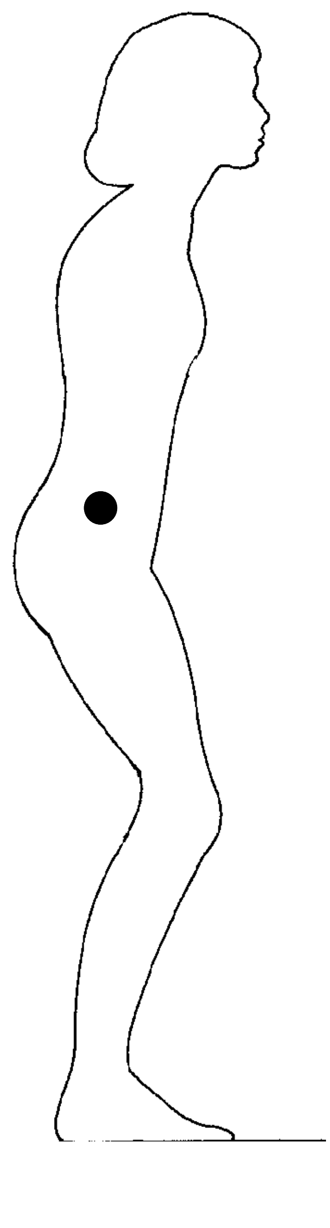
Walking

- Center of Mass
- Walking Kinematics
- Walking Kinetics
- Walking Energetics

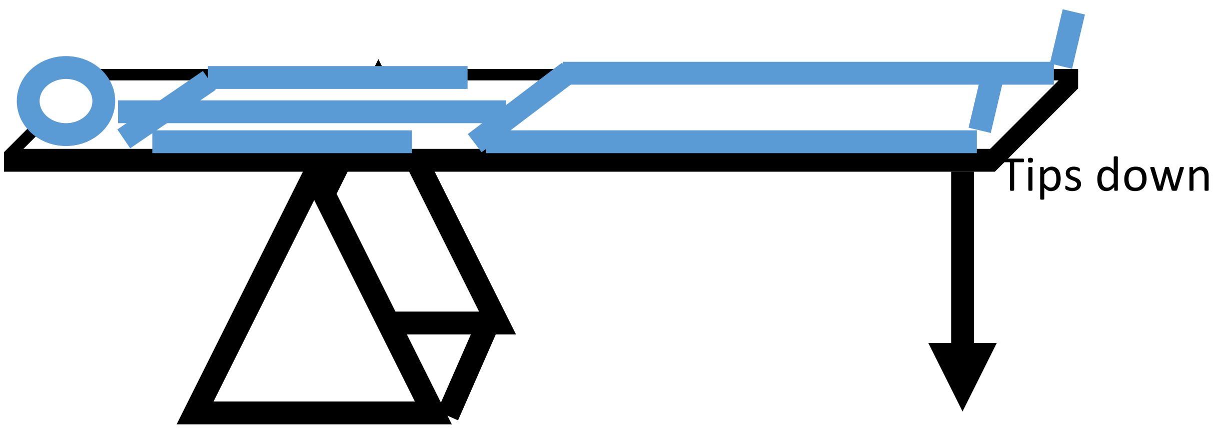
Center of mass (C.O.M.)

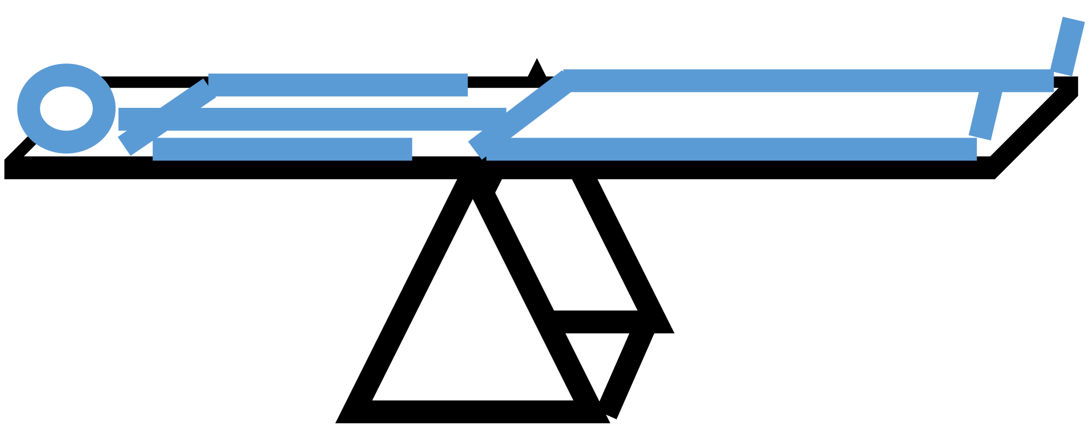
- A point about which all of the mass of an object is evenly distributed.
- Whole body can be represented by single point mass at C.O.M.

C.O.M. in standing person



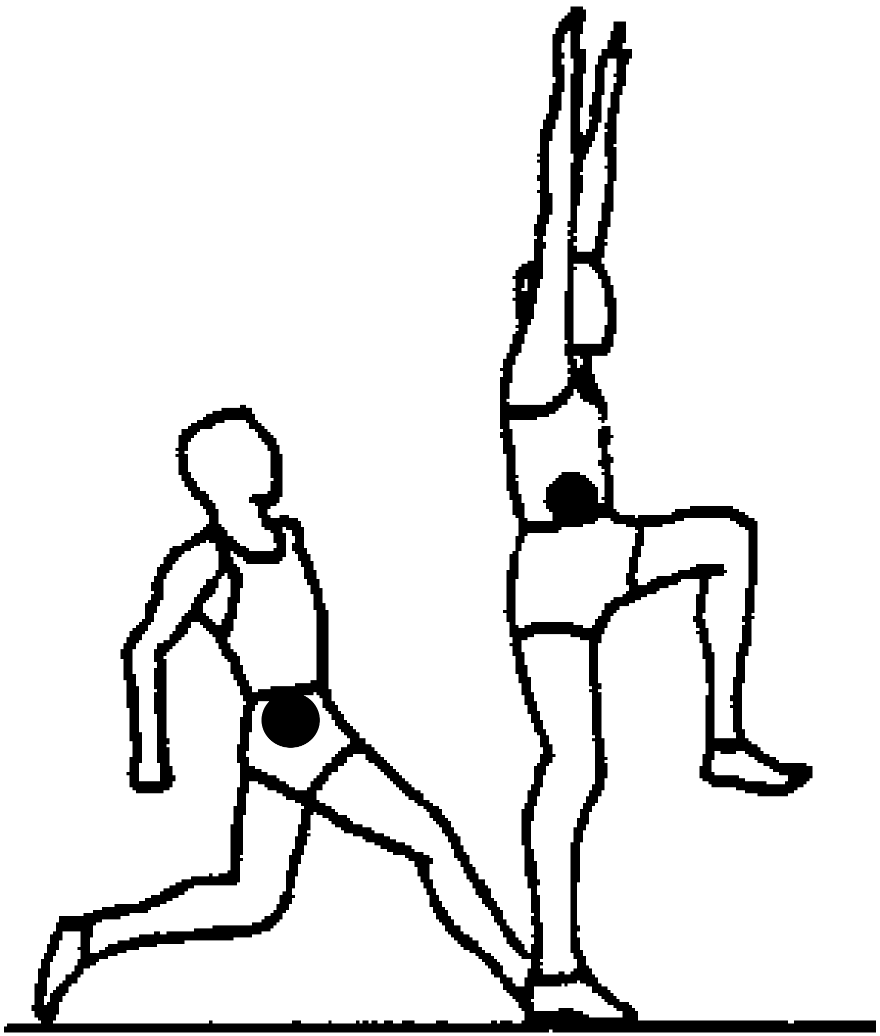
A crude method for finding C.O.M.





When balanced,
the C.O.M. position
been found

C.O.M. position can move.



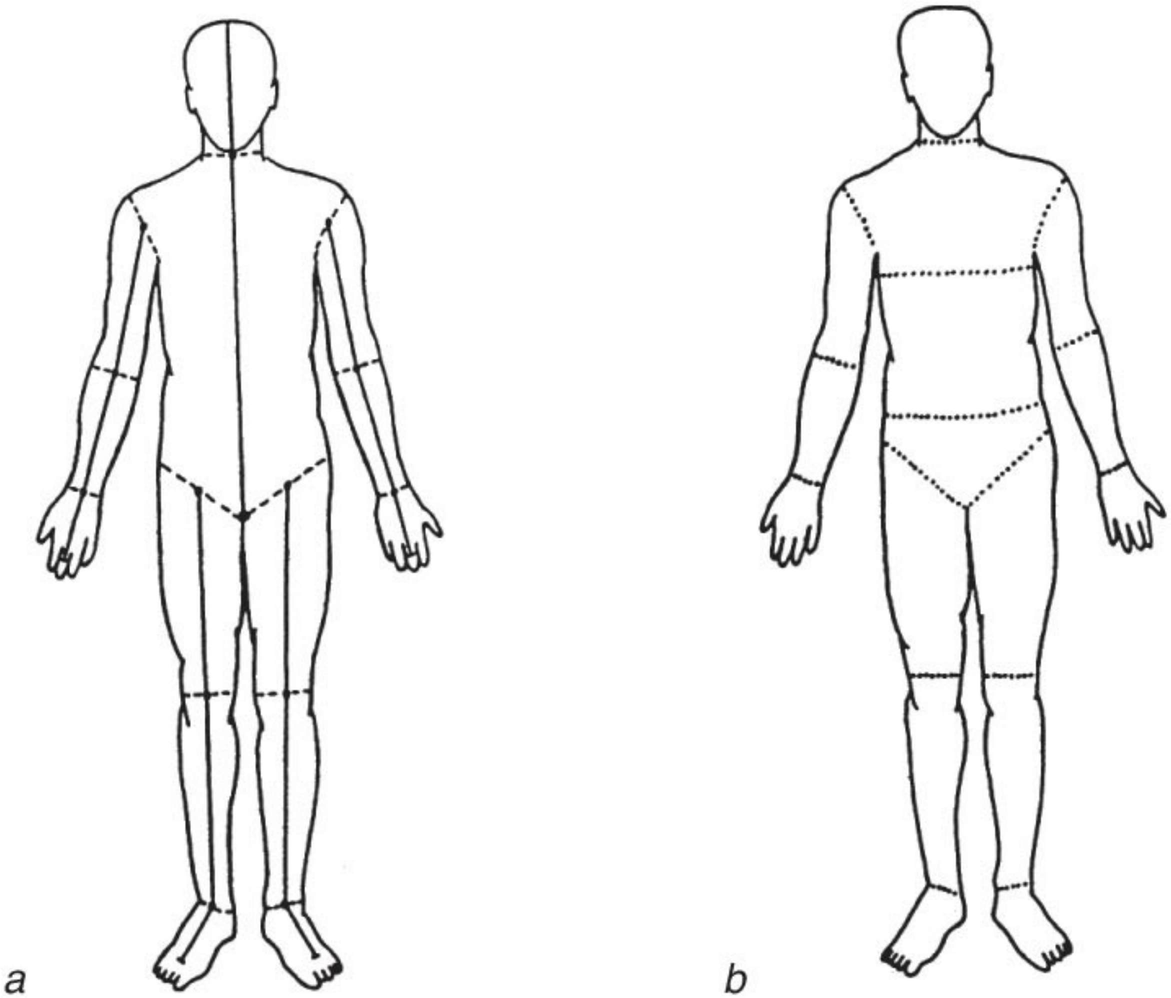
C.O.M. of whole body:
depends on the configuration of the body segments.

From Enoka 2.11

Neuromechanics of Human Movement

C.O.M. position depends on the distribution of body weight among and within the body segments

- Segmental analysis
  - head
  - trunk
  - upper arm
  - fore arm
  - hand
  - thigh
  - shank
  - foot



Enoka 2.13

Table 2.1 Regression Equations Estimating Body Segment Weights and Locations of the Center of Mass

Segment	Weight (N)	CM location (%)	Proximal end of segment
Head	$0.032\ F_w + 18.70$	66.3	Vertex
Trunk	$0.532\ F_w - 6.93$	52.2	C1
Upper arm	$0.022\ F_w + 4.76$	50.7	Shoulder joint
Forearm	$0.013\ F_w + 2.41$	41.7	Elbow joint
Hand	$0.005\ F_w + 0.75$	51.5	Wrist joint
Thigh	$0.127\ F_w - 14.82$	39.8	Hip joint
Shank	$0.044\ F_w - 1.75$	41.3	Knee joint
Foot	$0.009\ F_w + 2.48$	40.0	Heel

Note. Body segment weights are estimated from total-body weight (F_w), and the segmental center-of-mass (CM) locations are expressed as a percentage of segment length as measured from the proximal end of the segment.

Enoka Table 2.1

Segment mass

- Table 2.1 in Enoka - weights of segments and the position of the C.O.M. of segments.
- Example: thigh

  Thigh weight = 0.127*BW - 14.8

  Thigh weight and BW are in Newtons

  If person weighs 700N, then

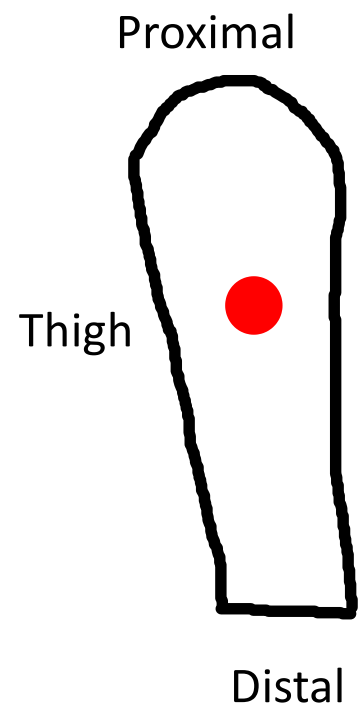
  Thigh weight = 74.08 N

Where is the C.O.M. of the thigh?

C.O.M. is ~ 40% of the distance from the proximal to the distal end of thigh

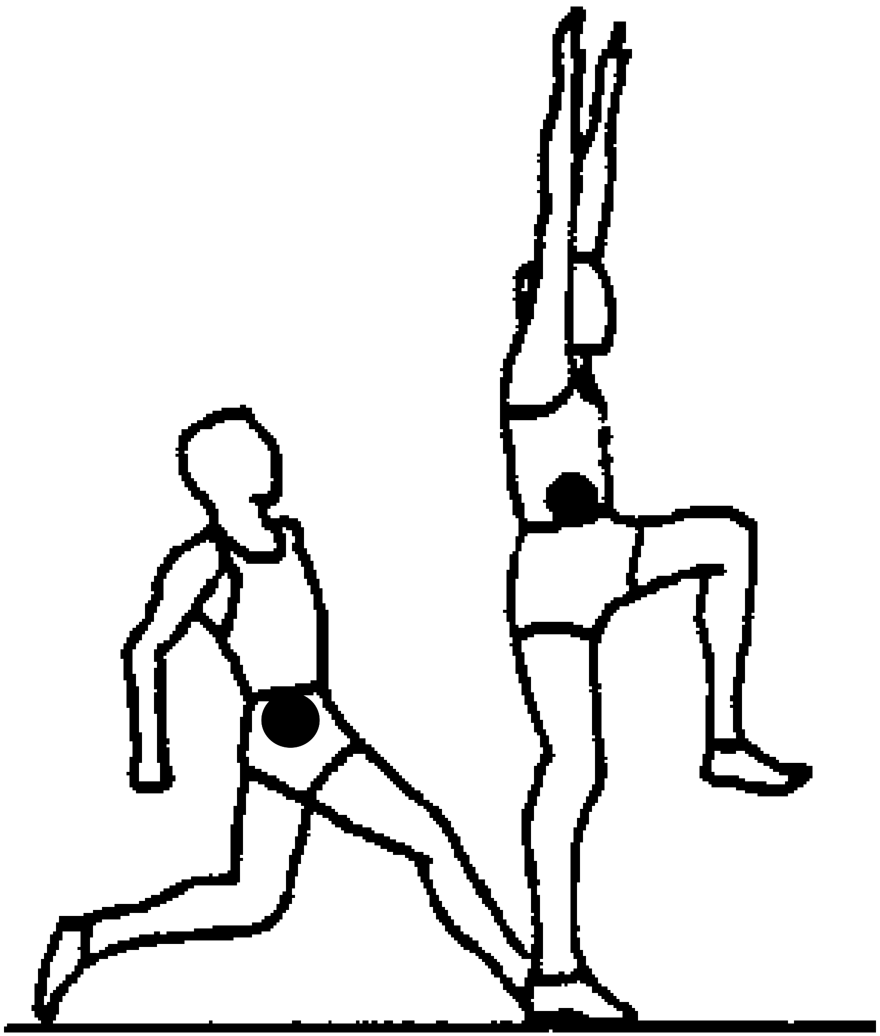
Proximal: Closer to trunk.

Distal: Further from trunk



C.O.M. can be located outside the body

How do we calculate the C.O.M. of more than one segment/object?



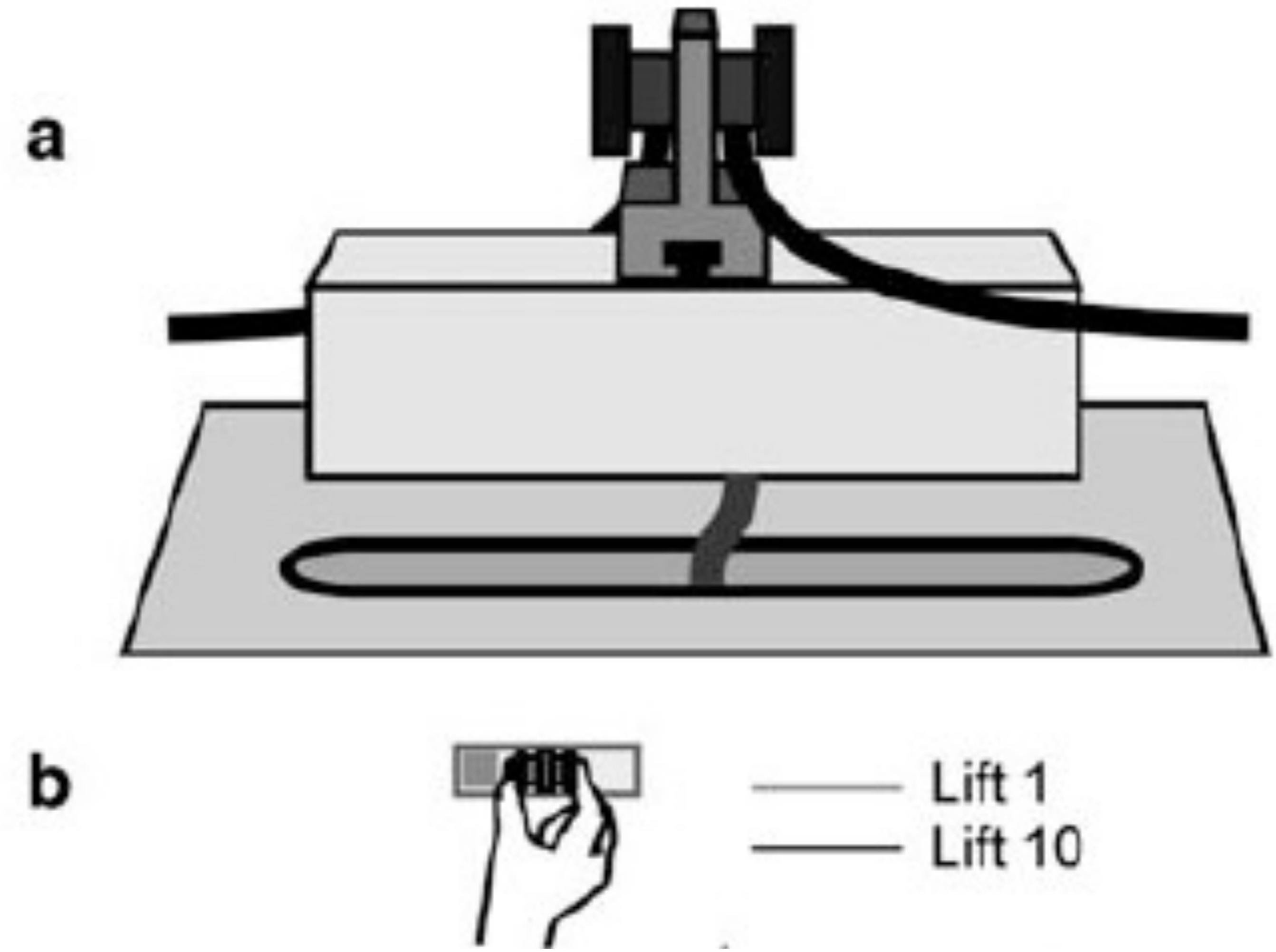
$$X_{COM} = \Sigma m_i x_i \,/ \Sigma m_i$$

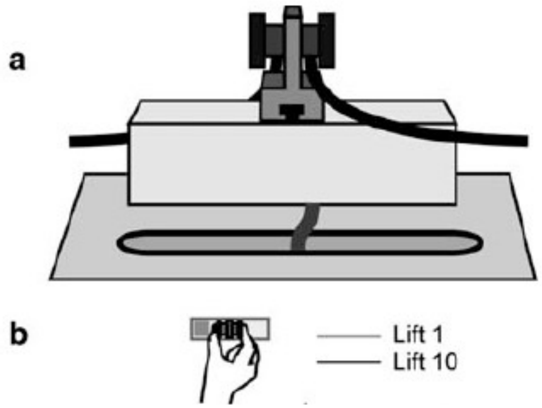
$$Y_{COM} = \Sigma m_i y_i / \Sigma m_i$$

$$X_{COM} = \frac{m_1 x_1 + m_2 x_2 + m_3 x_3}{m_1 + m_2 + m_3}$$

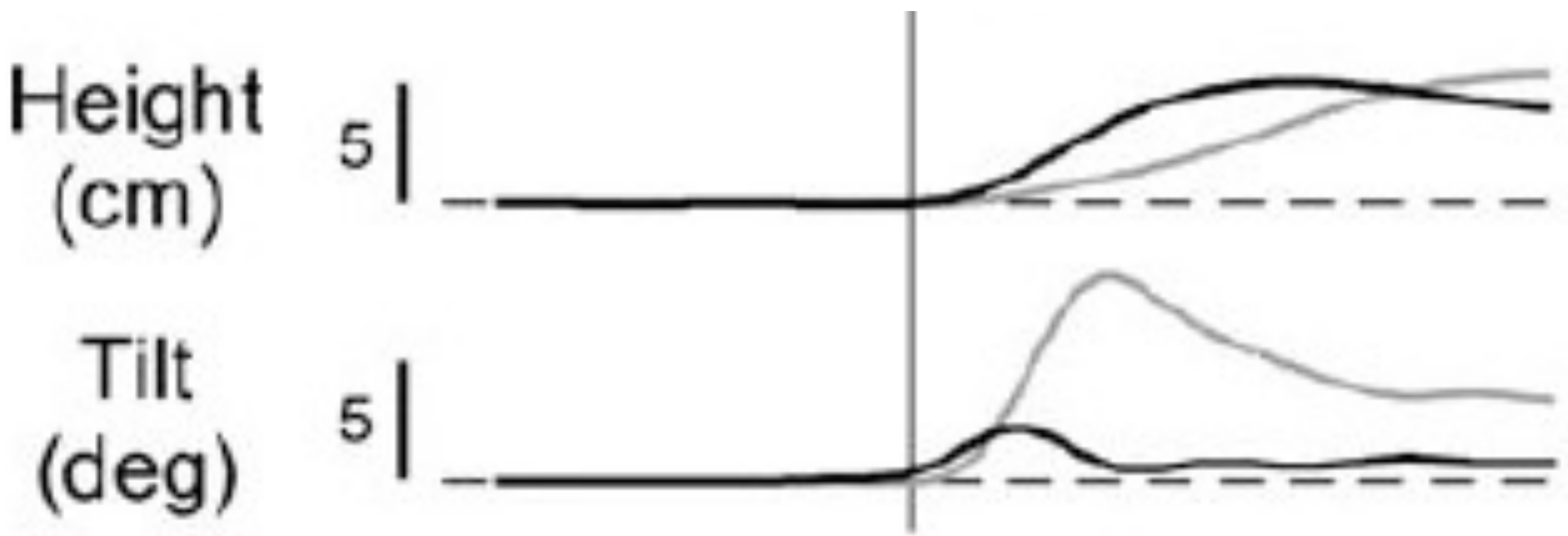
$$Y_{COM} = \frac{m_1 y_1 + m_2 y_2 + m_3 y_3}{m_1 + m_2 + m_3}$$

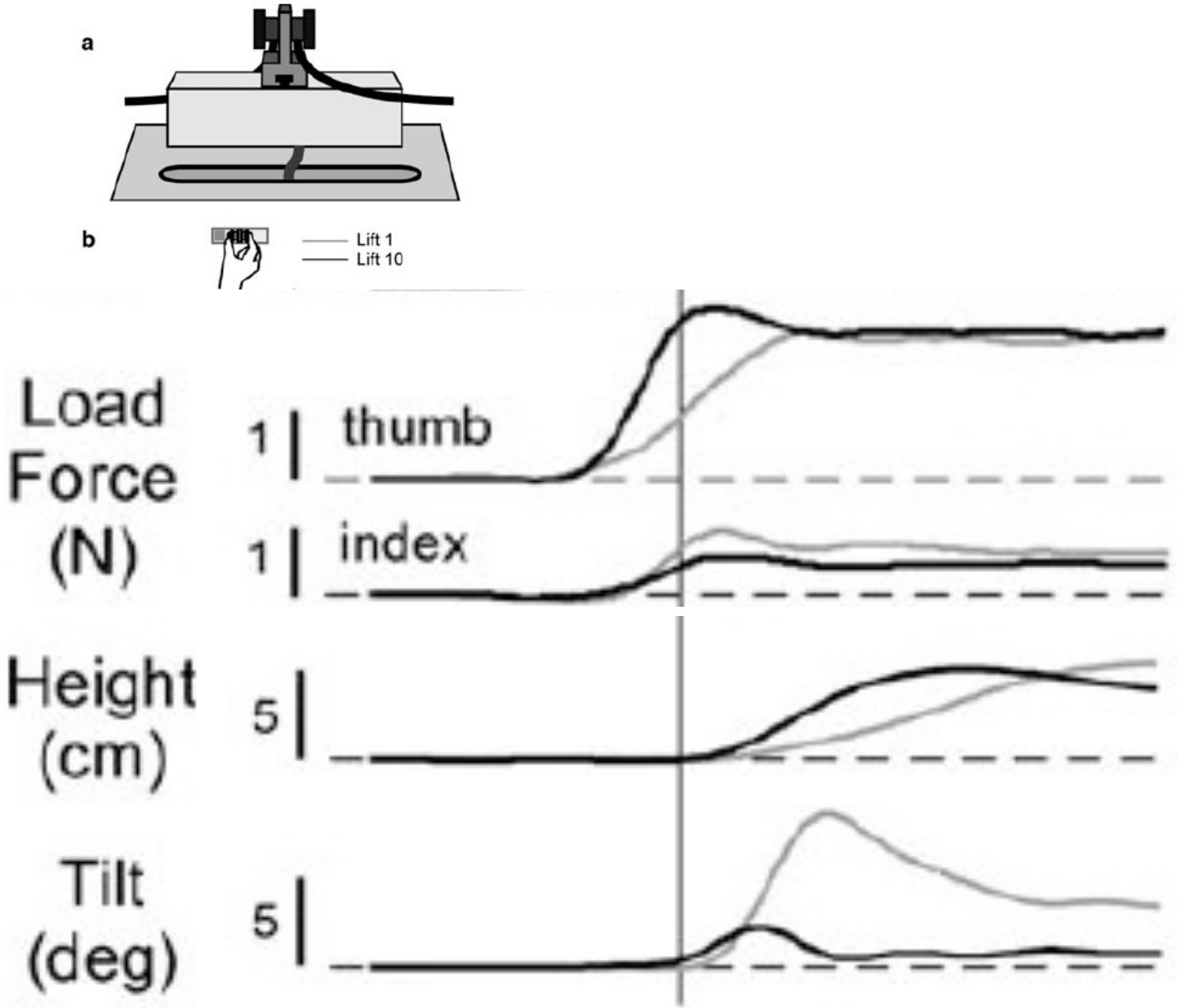
C.O.M. and the brain



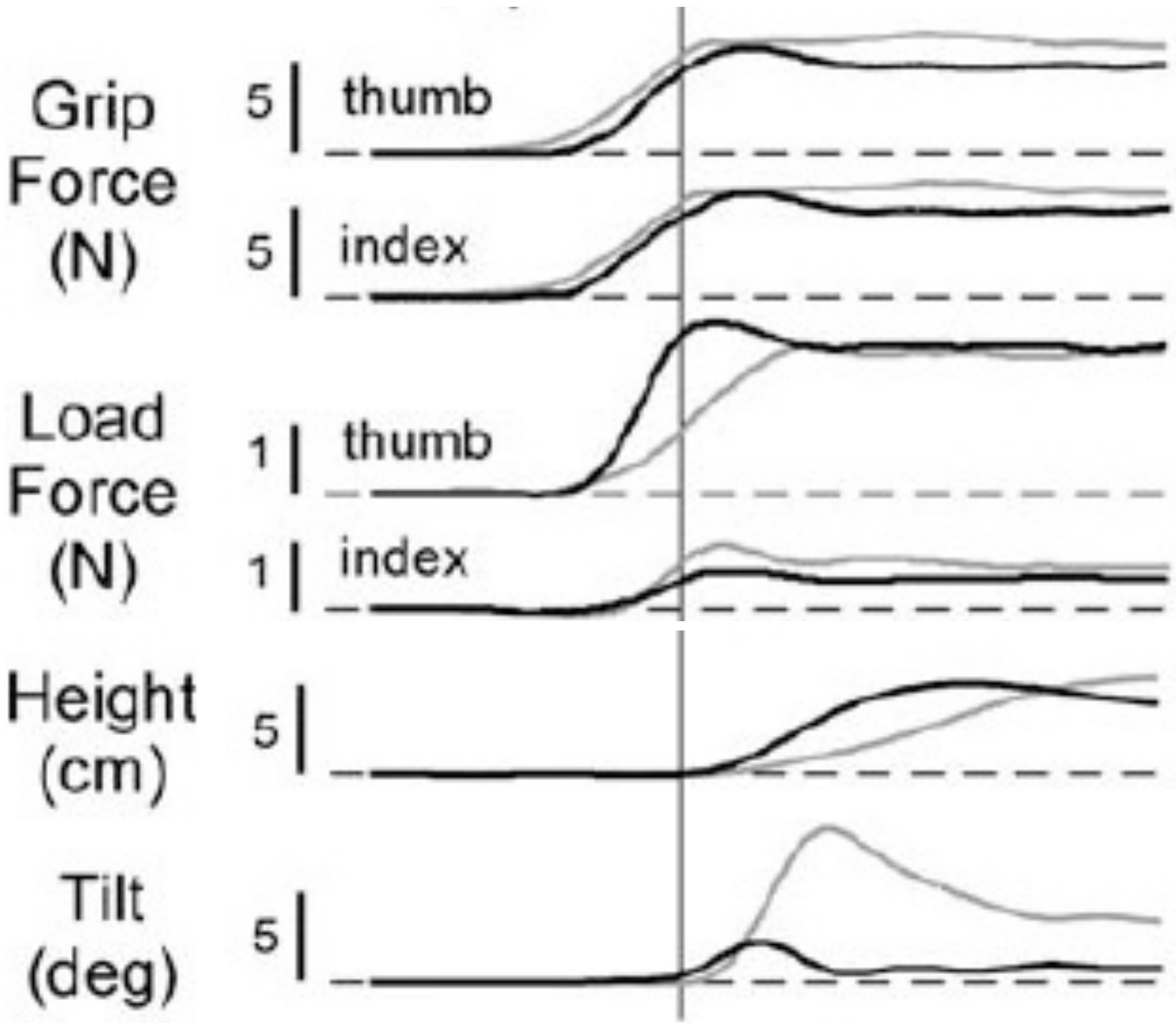


Lift 1
Lift 10



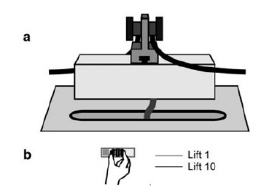


Lift 1
Lift 10



Lift 1

Lift 10



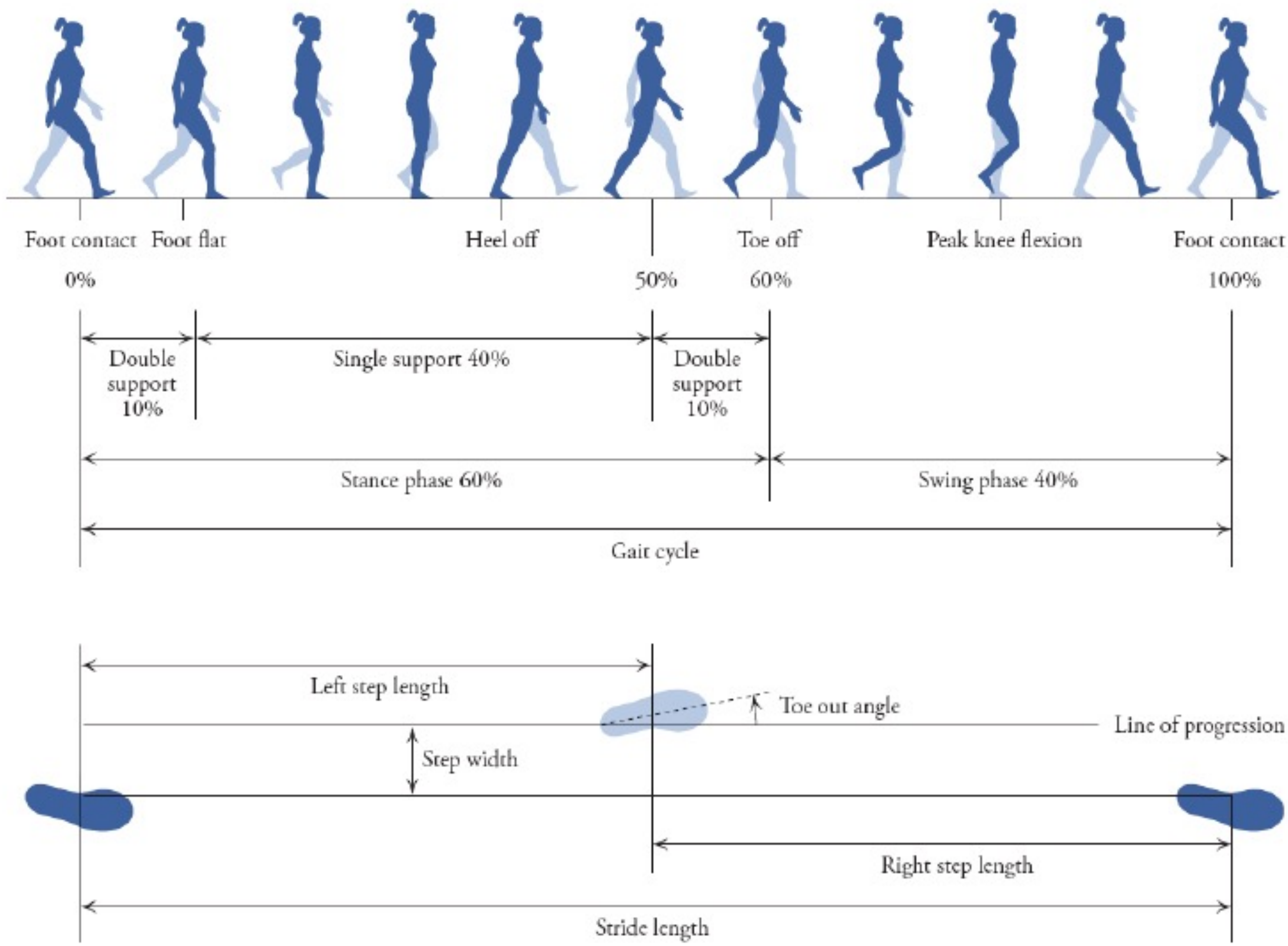
C.O.M and the brain

- Must know C.O.M. location for accurate object manipulation.
- Can observe initial learning over just a few tries.
- Robust learning over a timescale of years
  - Adults are better than children at estimating an object's center of mass

Walking

- Center of Mass
- Walking Kinematics
- Walking Kinetics
- Walking Energetics

Walking gait cycle



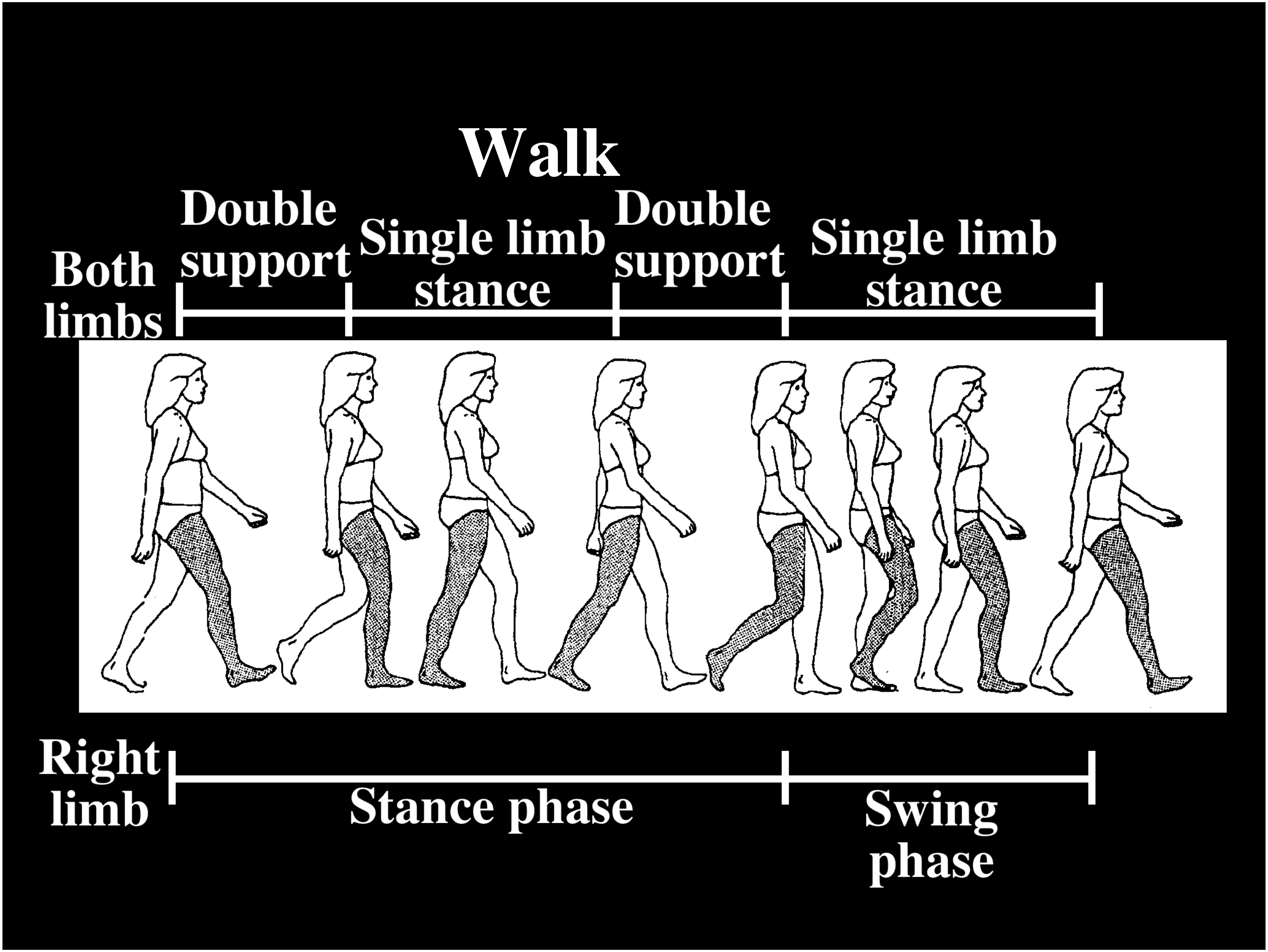
Kinematic terms for gait analysis

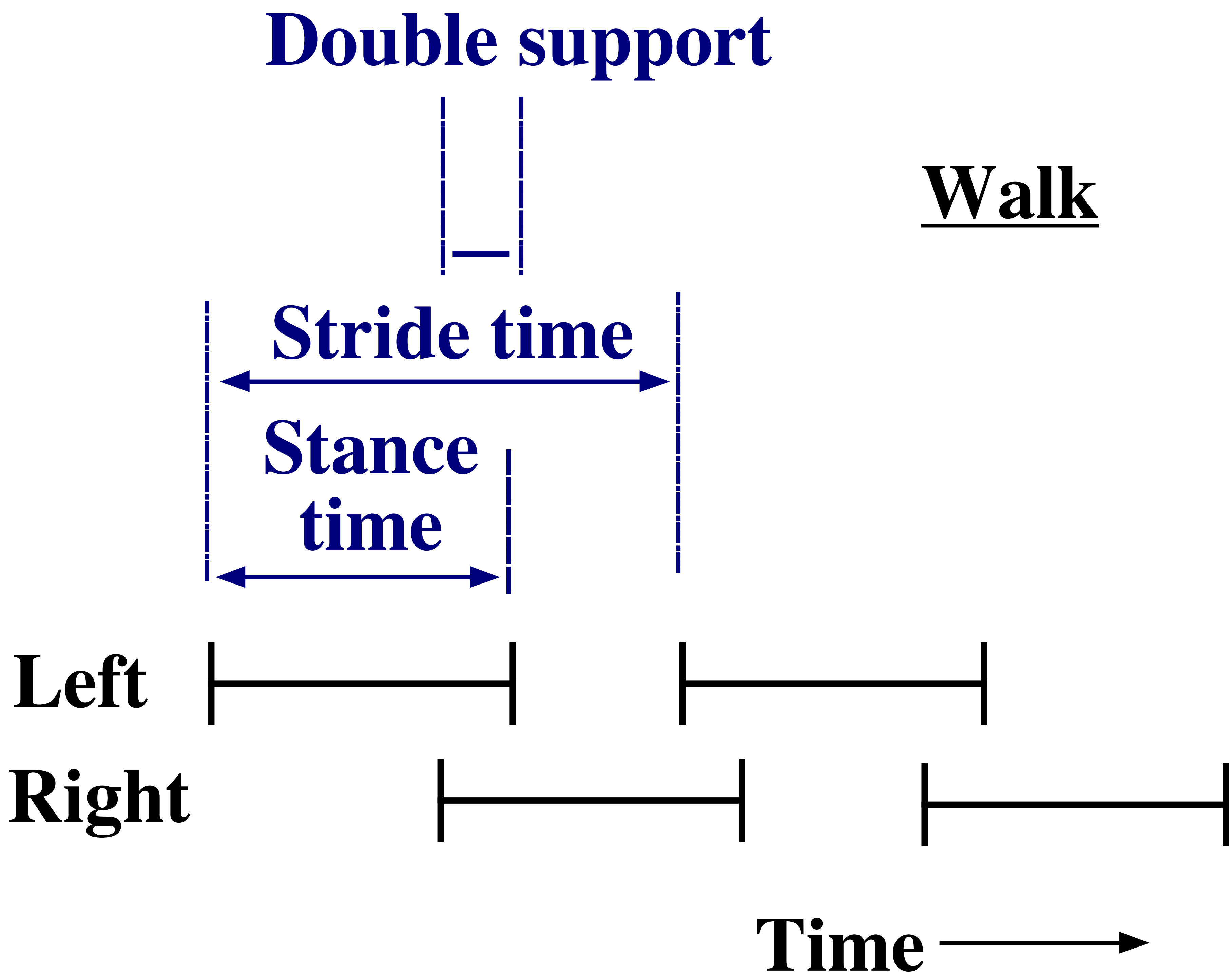
<u>Stride</u>: One complete cycle from an event (e.g., right foot touch-down) to the next time that event occurs.

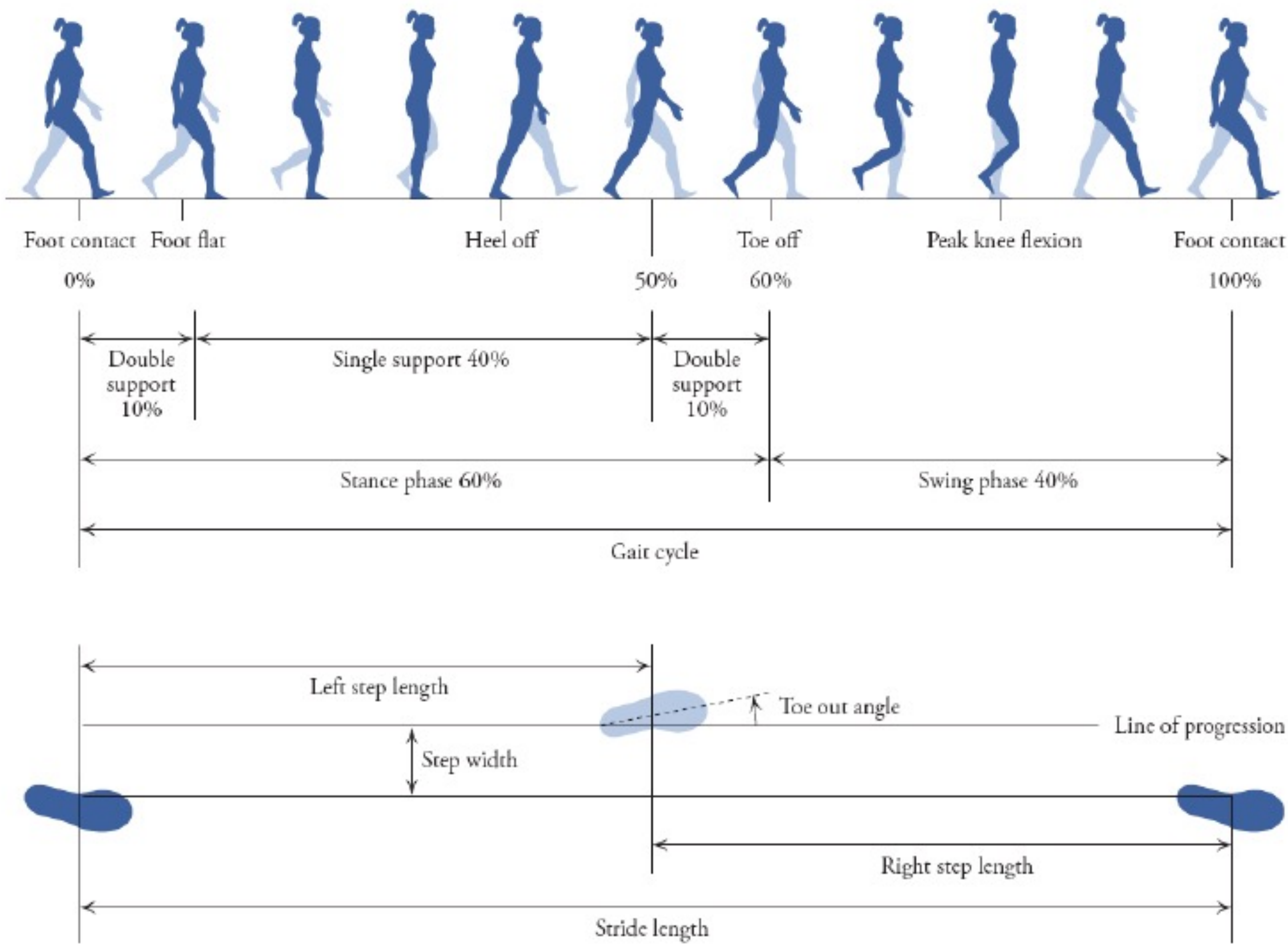
<u>Stance phase</u>: Time when a limb is in contact with the ground.

Kinematic terms for gait analysis

<u>Double support</u>: Time when 2 limbs are in contact with the ground.


Walk
Both limbs
Double support
Single limb stance
Double support
Single limb stance
Right limb
Stance phase
Swing phase


Double support
Walk
Stride time
Stance
time
Left
Right
Time


Foot contact
Foot flat
Heel off
Toe off
Peak knee flexion
Foot contact
0%
50%
60%
100%
Double support 10%
Single support 40%
Double support 10%
Stance phase 60%
Swing phase 40%
Gait cycle
Left step length
Toe out angle
Line of progression
Step width
Right step length
Stride length

Speed = SF * SL

Speed (m/s) = SF (strides/s) * SL (m/strides)

stride frequency: number of strides per second

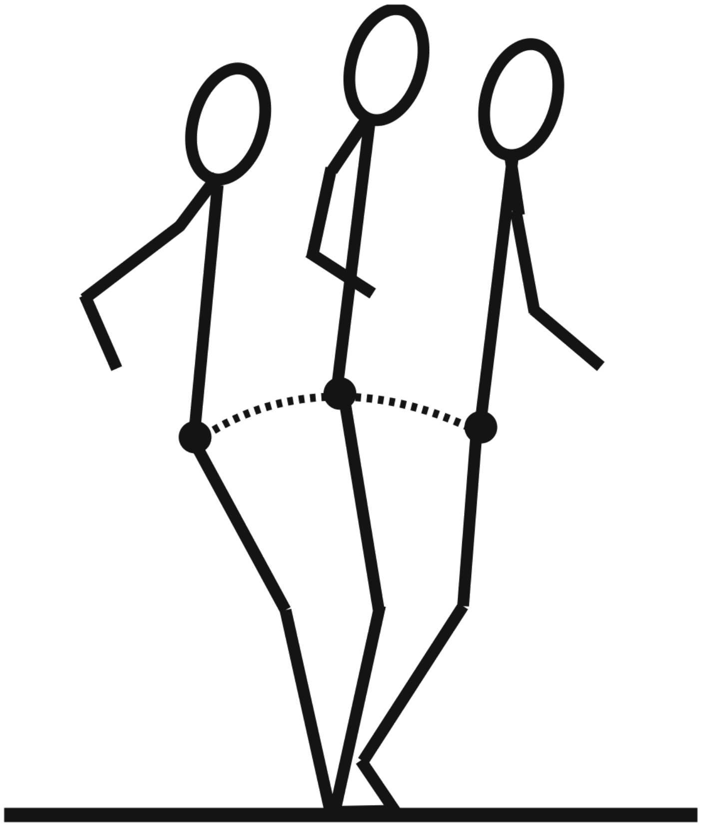
stride length: distance covered by one stride

Can increase speed by increasing SF, SL or both

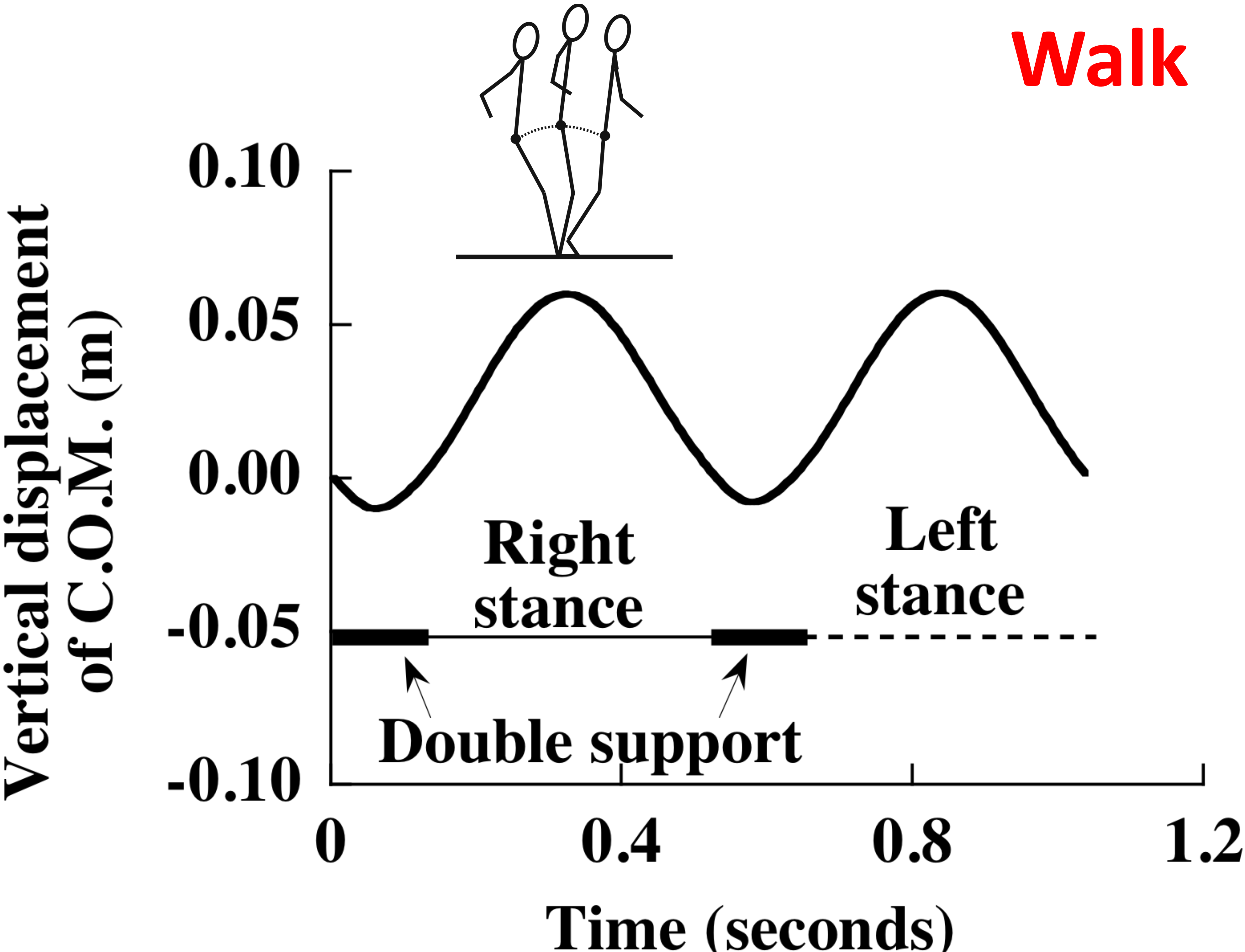
Walking kinematics

- Components of a stride
- Vertical displacement of the body
- Horizontal velocity of the body

Walk



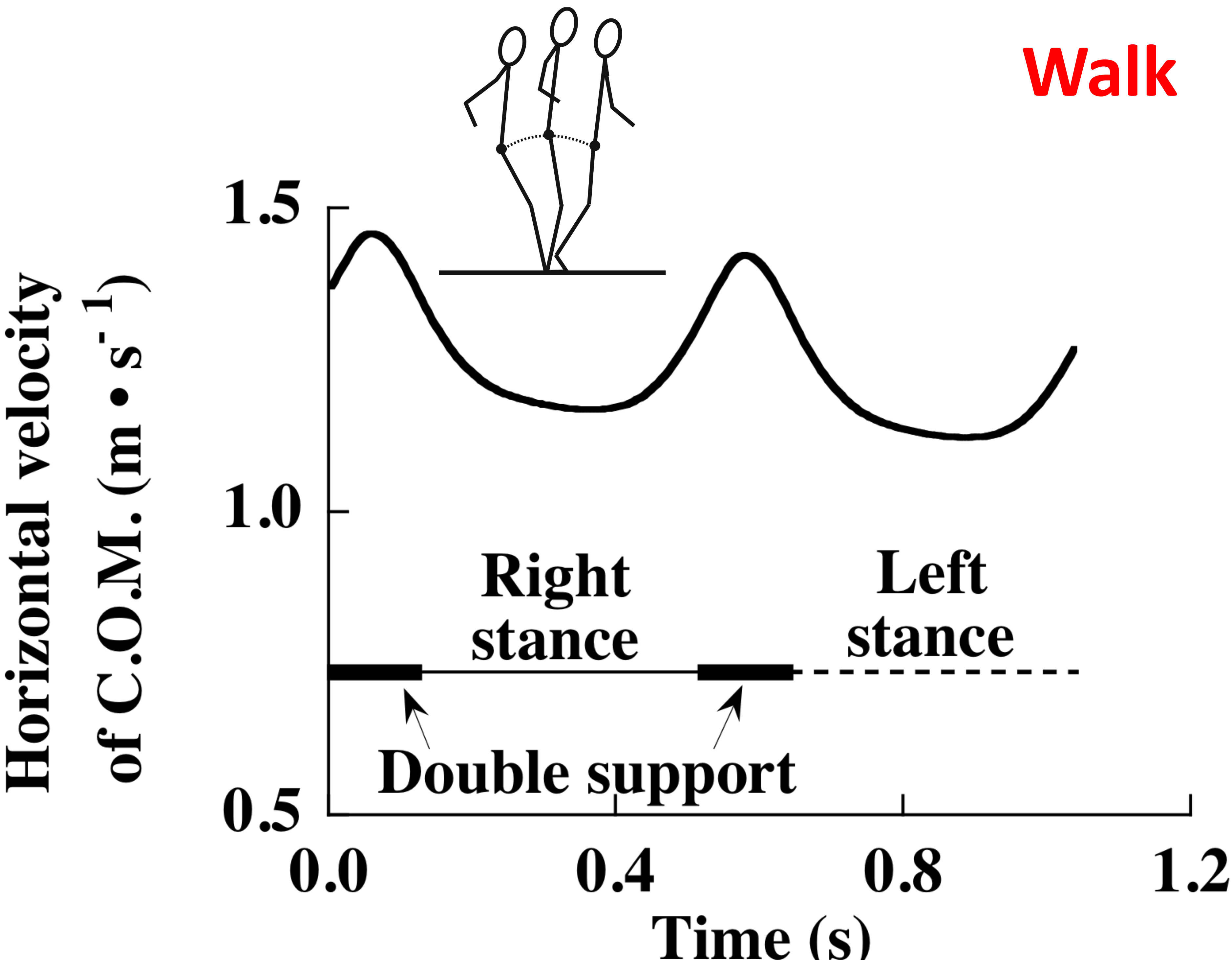
- Hip highest at mid-stance.
- Leg is straighter.



Walk
0.10
0.05
0.00
-0.05
-0.10
Vertical displacement of C.O.M. (m)
Right stance
Left stance
Double support
0
0.4
0.8
1.2
Time (seconds)

Walking kinematics

- Components of a stride
- Vertical displacement of the body
- Horizontal velocity of the body

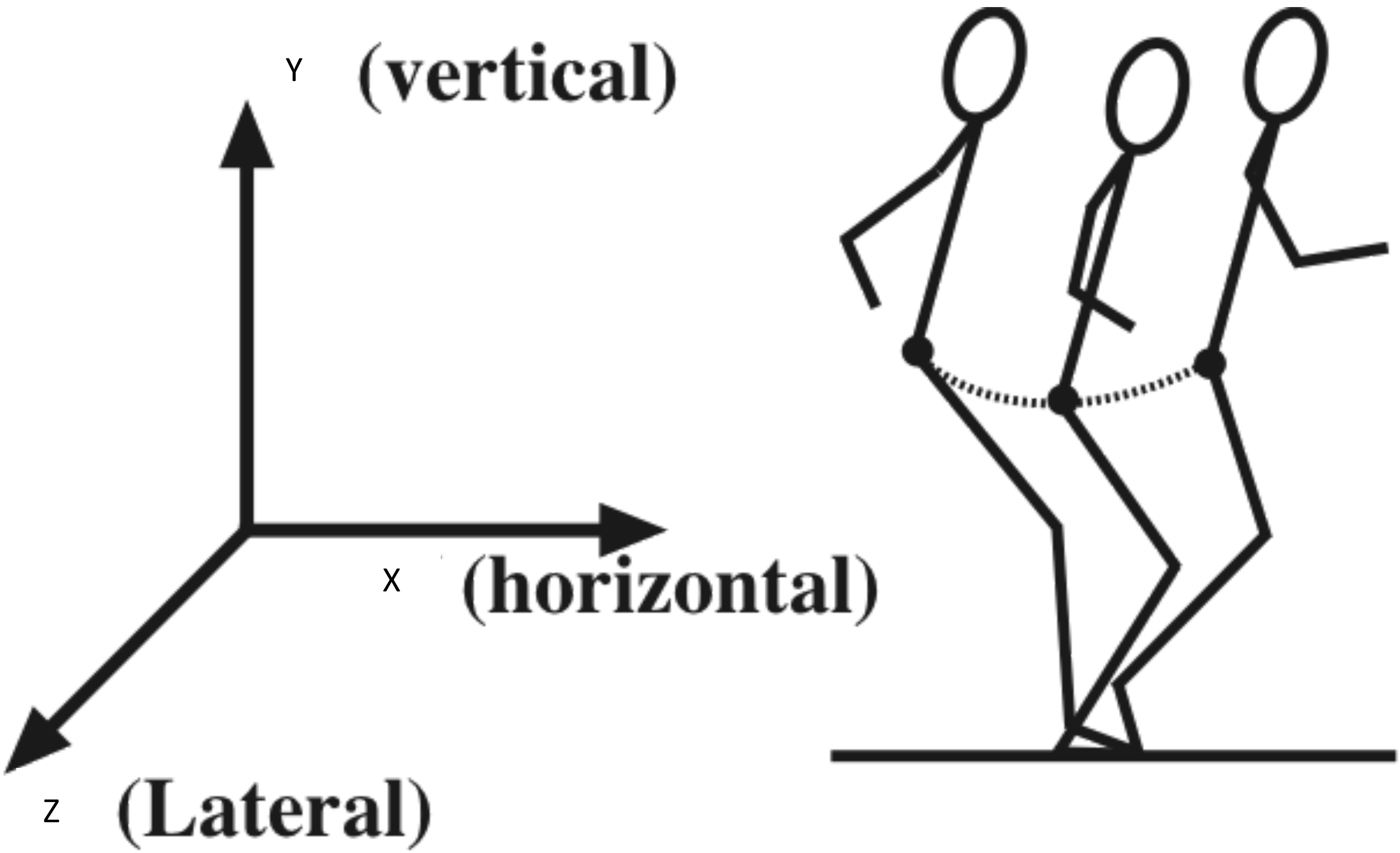

Walk
1.5
1.0
0.5
Horizontal velocity of C.O.M. (m • s-1)
Right stance
Left stance
Double support
0.0
0.4
0.8
1.2
Time (s)

Walking

- Center of Mass
- Walking Kinematics
- Walking Kinetics
- Walking Energetics

Walking Kinetics

- Measurement of ground reaction forces
- Analysis of ground reaction forces
- Walking GRFs



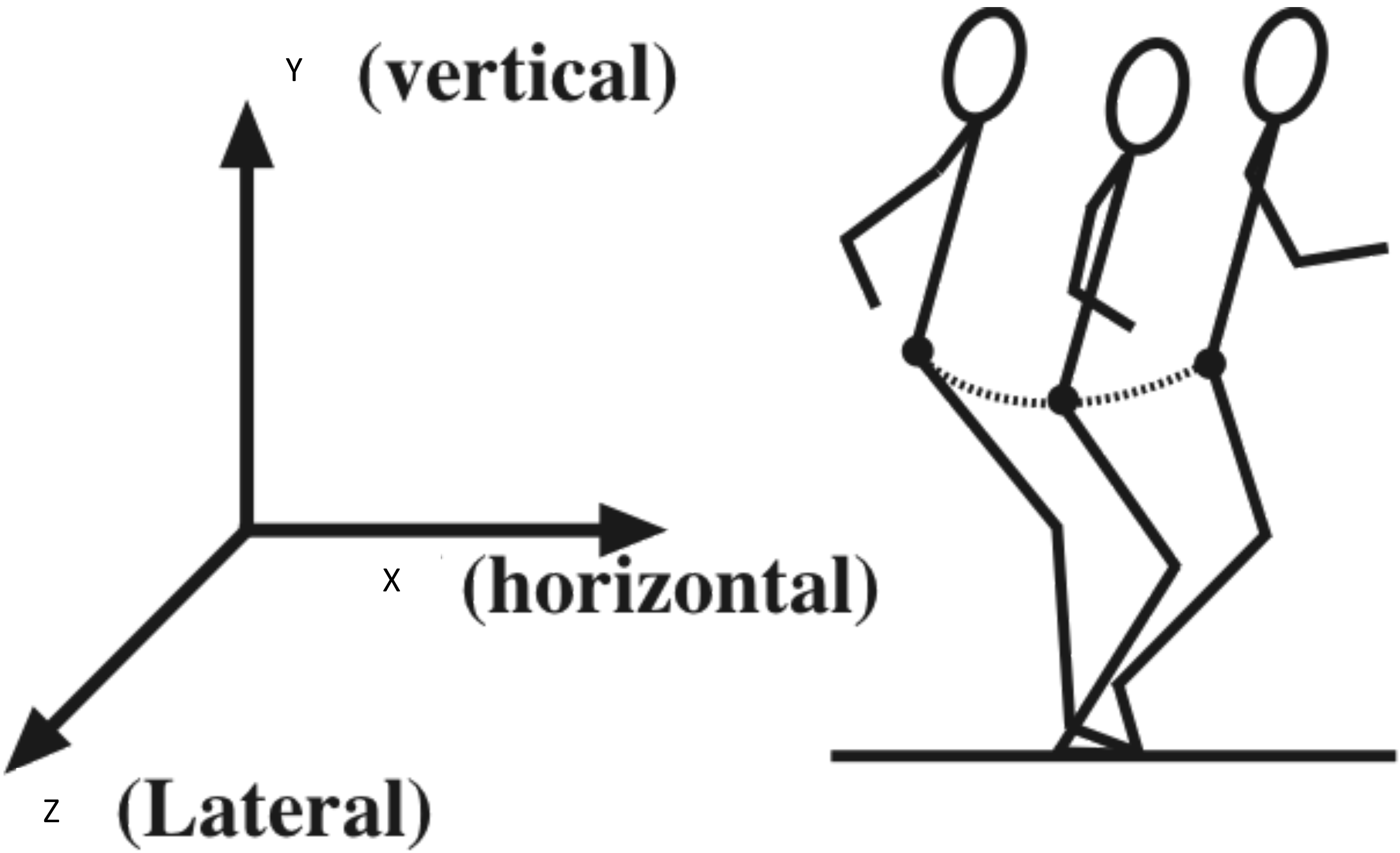
Y
(vertical)
X
(horizontal)
Z
(Lateral)

Measurement of ground reaction force

- Static: a <u>bathroom scale</u> can be used.
- Dynamic (e.g., jump): a <u>force platform</u> should be used.

Force platform

- Can measure forces very quickly (e.g., every 0.0001 s).
- Can measure the forces in three dimensions
  - Vertical: $F_{g,y}$
  - Horizontal: $F_{g,x}$
  - Lateral: $F_{g,z}$


Y
(vertical)
X
(horizontal)
Z
(Lateral)

Sign convention for $F_{g,y}$

- $F_{g,y}$

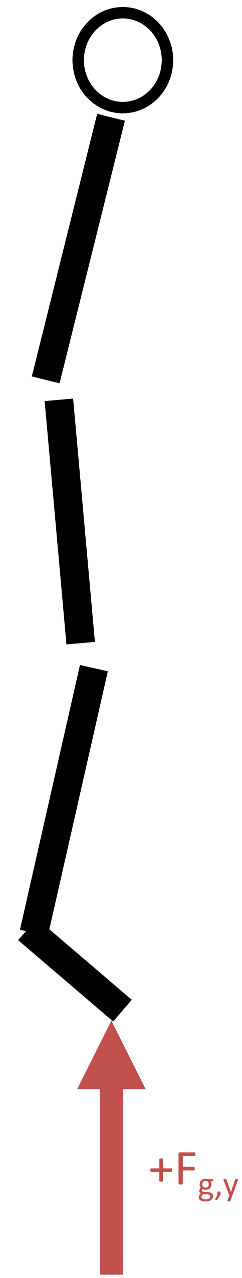
  Upward is positive

  Locomotion, jumping, etc.:

  $F_{g,y} > 0$

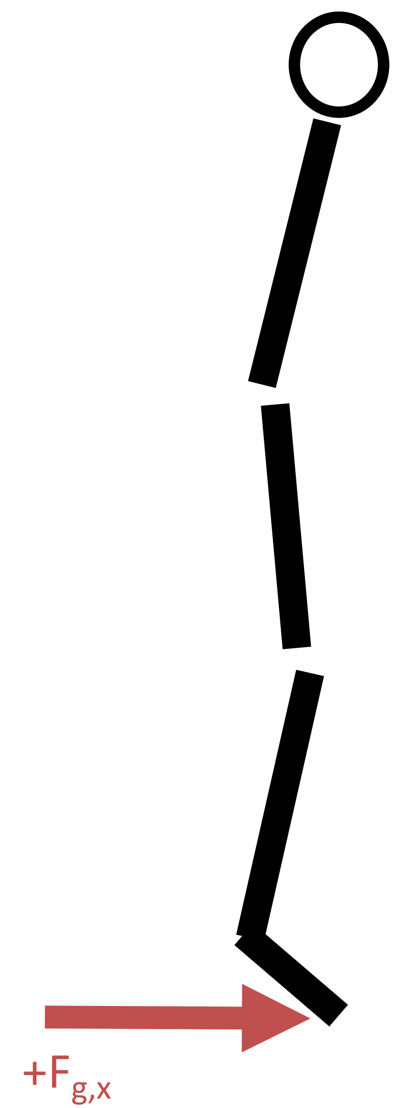
  $F_{g,y} < 0$: not normally possible

  need suction cup shoes



Sign conventions

- Positive $F_{g,x}$: oriented in the direction of motion or toward anterior side.



Analysis of ground reaction forces

- Can be used to calculate

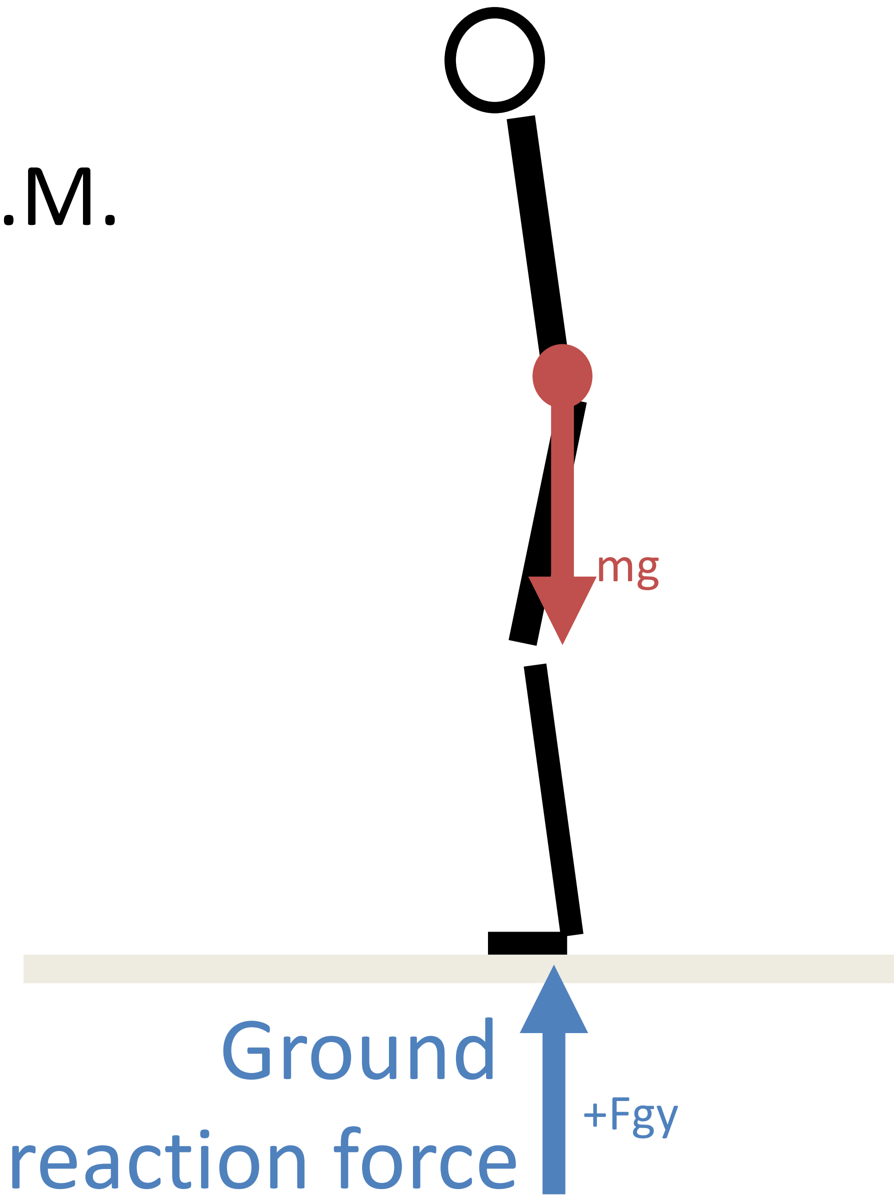
the acceleration of the C.O.M.

$\Sigma F = ma$

$\Sigma F_y = ma_y$

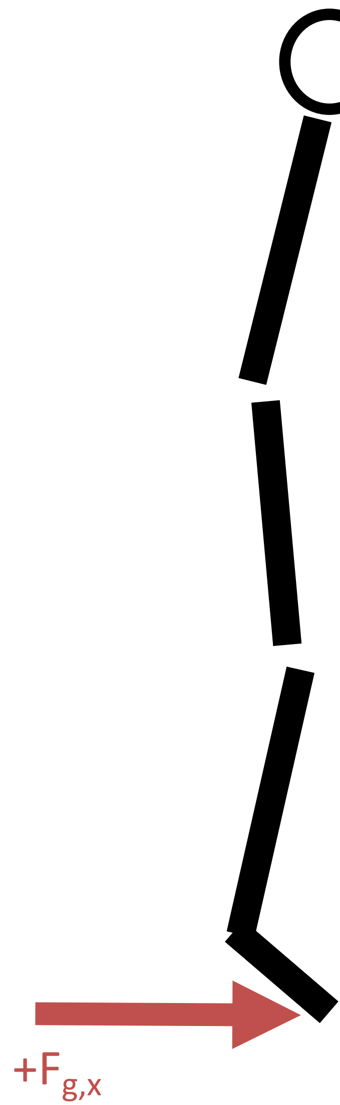
$F_{g,y} - mg = ma_y$

$F_{g,y} = ma_y + mg$



Analysis of ground reaction forces

- Can be used to calculate the acceleration of the C.O.M.



$\Sigma F = ma$

$\Sigma F_x = ma_x$

$F_{g,x} = ma_x$

Analysis of ground reaction forces

- Can be used to calculate the acceleration of the C.O.M.

$\Sigma F = ma$

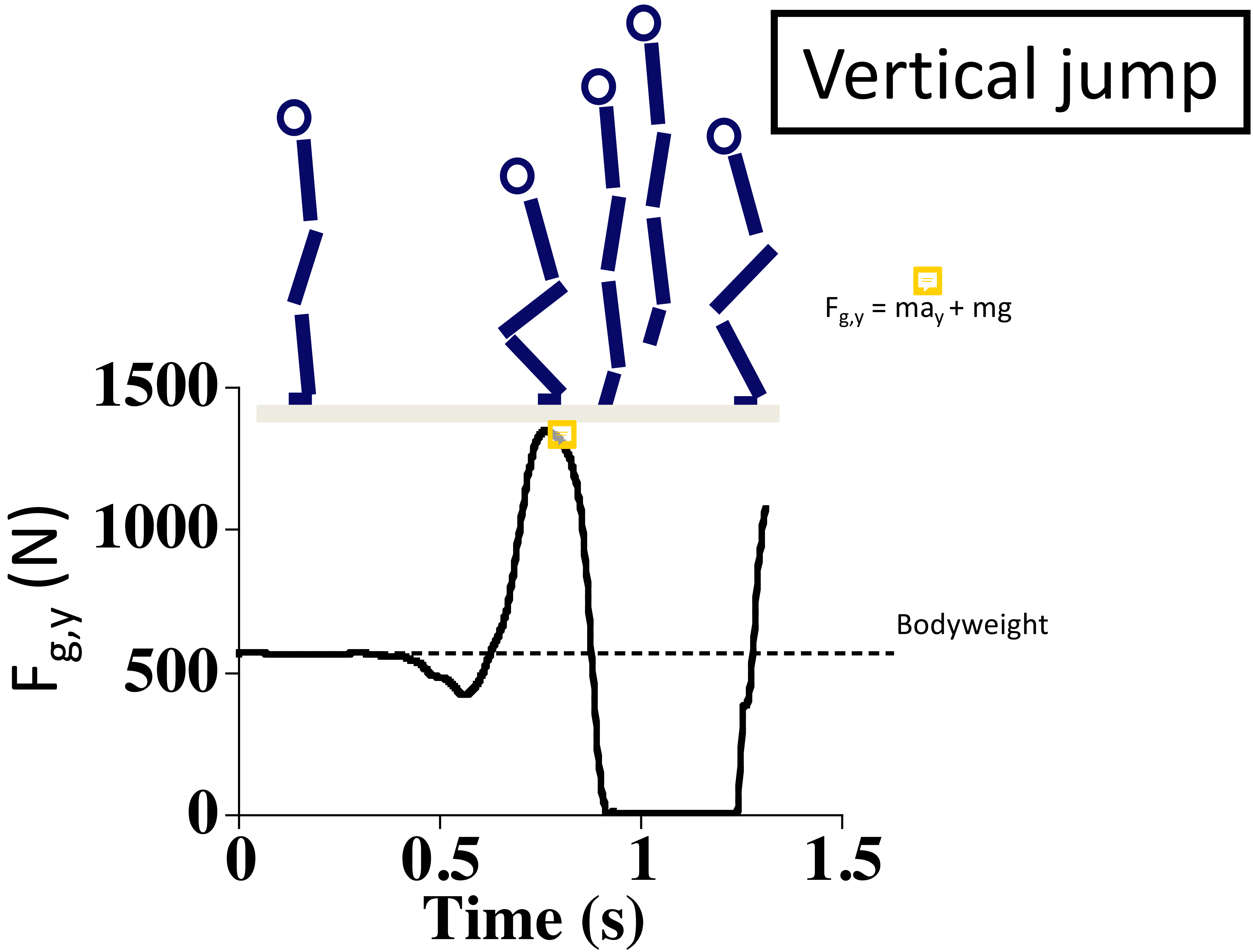
$\Sigma F_y = ma_y$

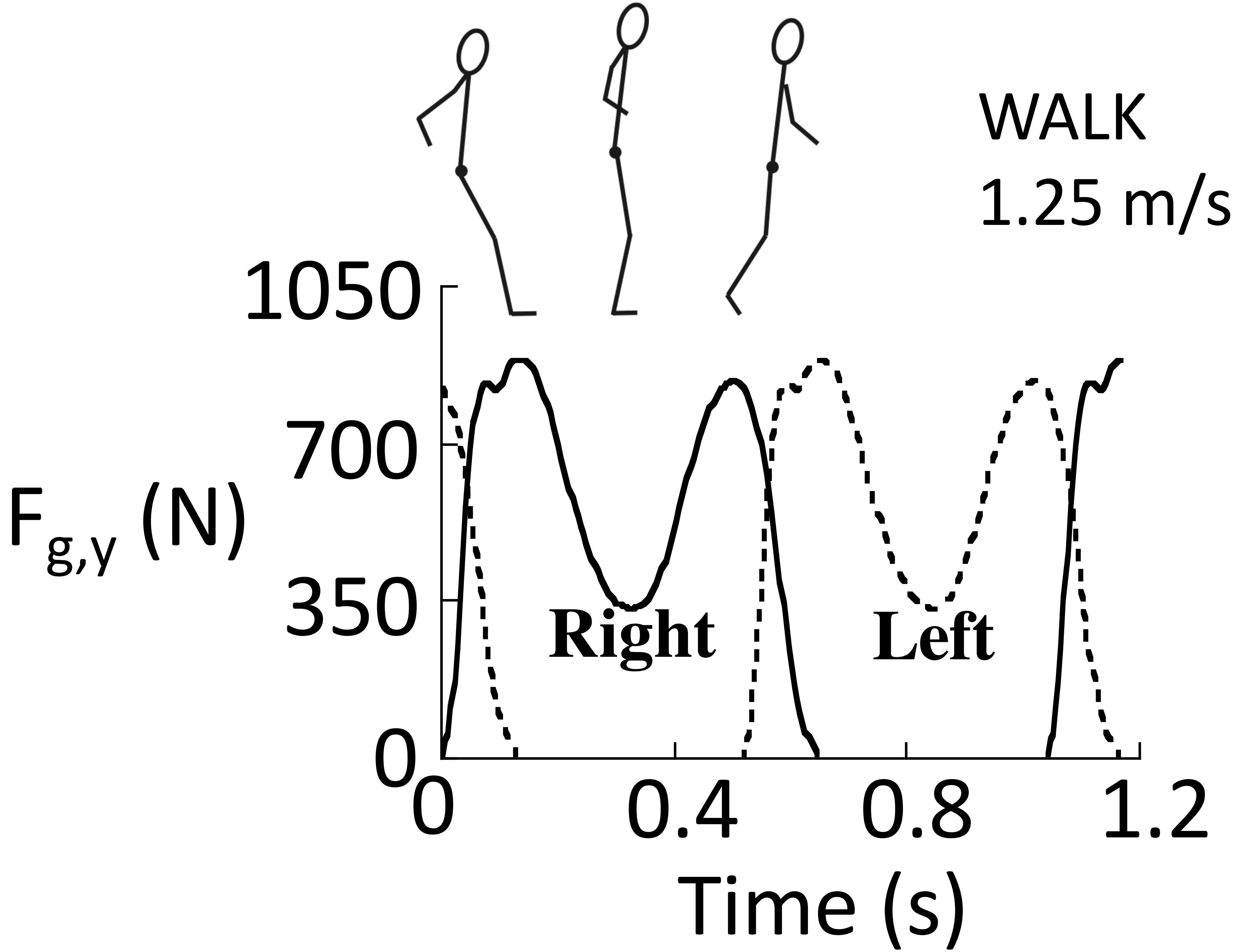
$\Sigma F_x = ma_x$

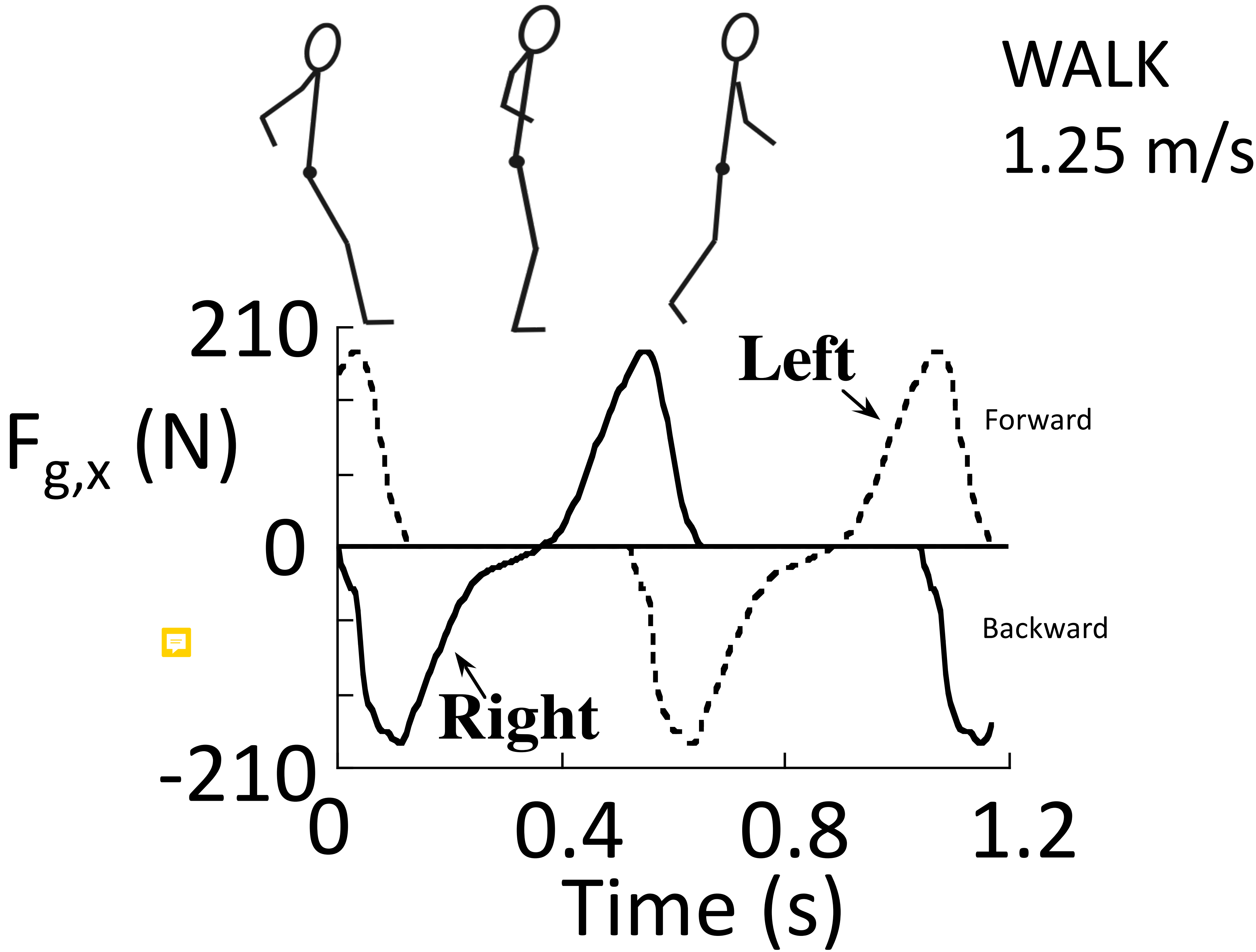
$F_{g,y} - mg = ma_y$

$F_{g,y} = ma_y + mg$

$F_{g,x} = ma_x$


Vertical jump
$F_{g,y} = ma_y + mg$
Bodyweight
1500
1000
500
0
$F_{g,y}$ (N)
0
0.5
1
1.5
Time (s)


WALK
1.25 m/s
$F_{g,y}$ (N)
1050
700
350
0
0
0.4
0.8
1.2
Time (s)
Right
Left


WALK
1.25 m/s
210
$F_{g,x}$ (N)
0
-210
Left
Right
Forward
Backward
0
0.4
0.8
1.2
Time (s)

Walking

- Center of Mass
- Walking Kinematics
- Walking Kinetics
- Walking Energetics

Mechanical energy in level walking

Some kinetic energy

Some gravitational potential energy

Little work done against aerodynamic drag

Unless slipping, no work done against friction

Not much bouncing (elastic energy)

Calculating mechanical energy

- Obtain acceleration from force plate recording
- Integrate acceleration once and twice to estimate center of mass velocity and position.
- Kinetic Energy (f = forward):

$$E_{\mathrm{kf}} = \tfrac{1}{2} m_{\mathrm{body}} v_{\mathrm{COM,f}}^2 = \tfrac{1}{2} m_{\mathrm{body}} \left(\int a_{\mathrm{COM,f}}(t)\, \mathrm{d}t \right)^2$$

- Potential Energy (v = vertical):

$$E_{\mathrm{pg}} = m_{\mathrm{body}}\, g\, r_{\mathrm{COM,v}} = m_{\mathrm{body}}\, g \iint a_{\mathrm{COM,v}}(t)\, \mathrm{d}^2 t$$

Mechanical energy fluctuations in level walking

Average KE constant (average v_x constant)

Average GPE constant (average r_y constant)

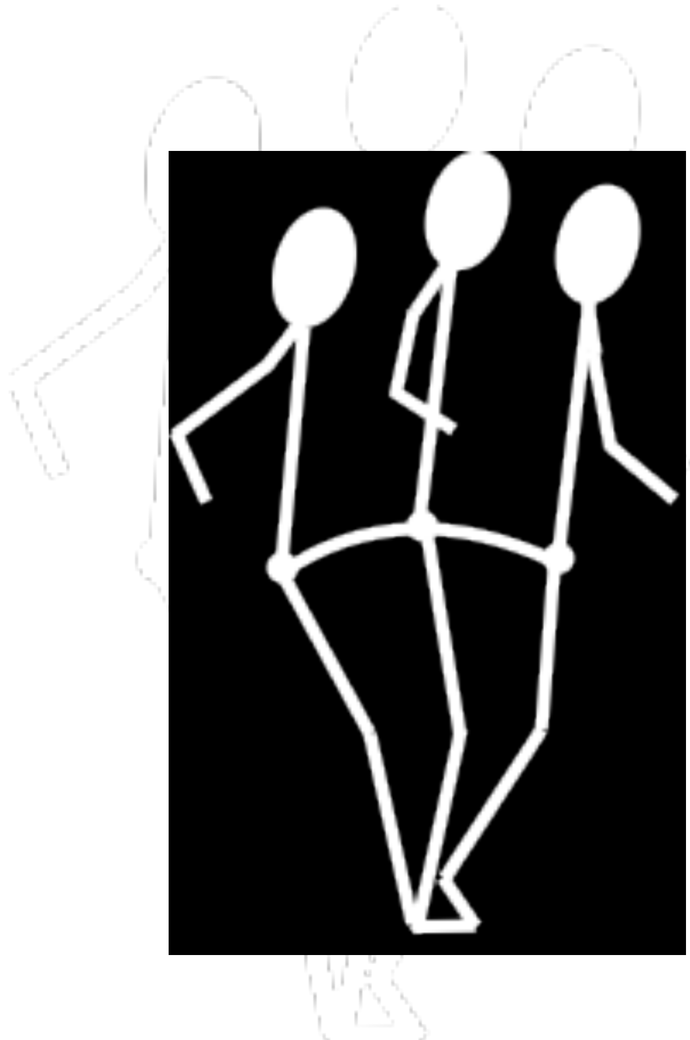
HOWEVER

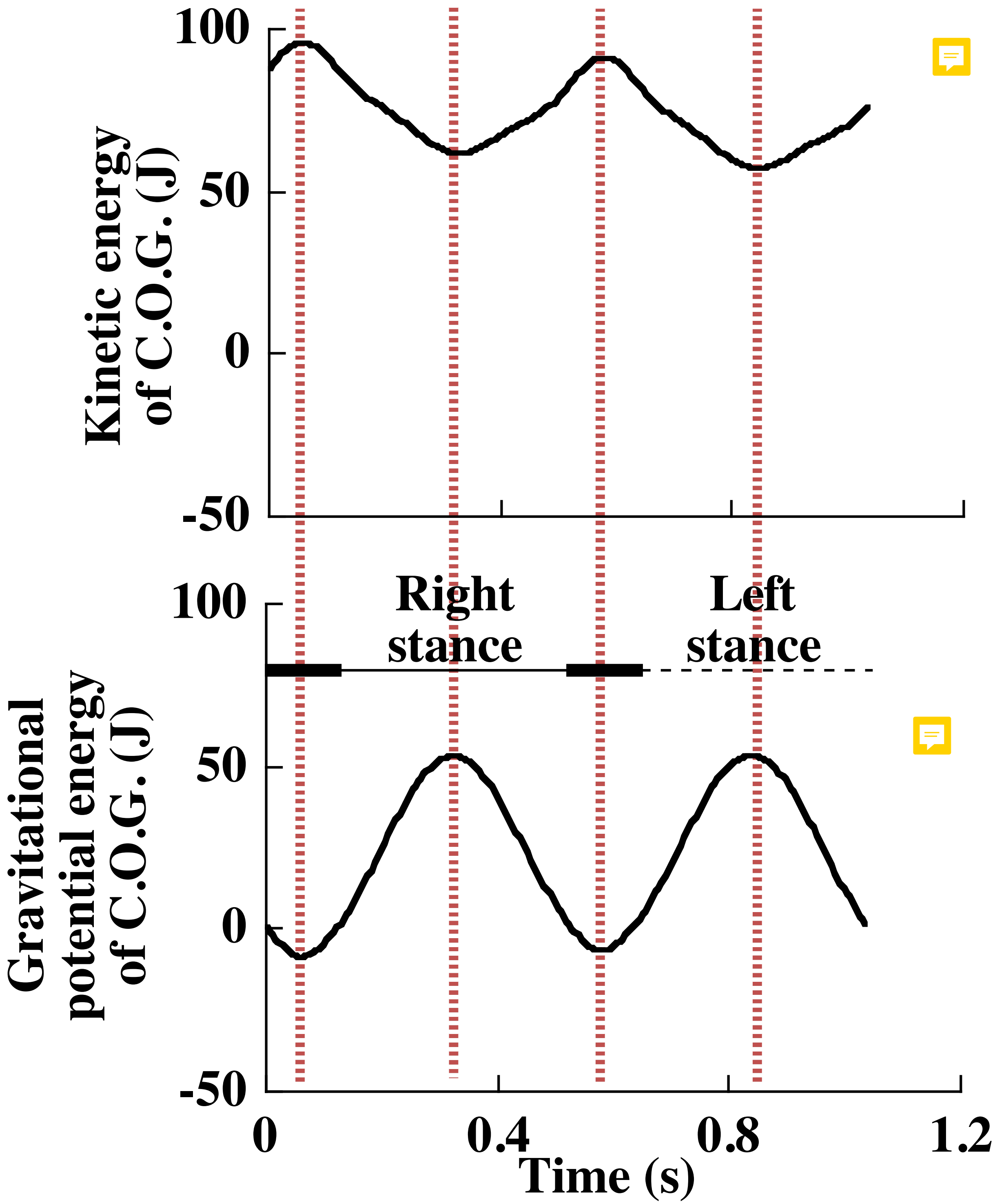
- KE and GPE fluctuate within each stance

Walk

v_x decreases
r_y increases

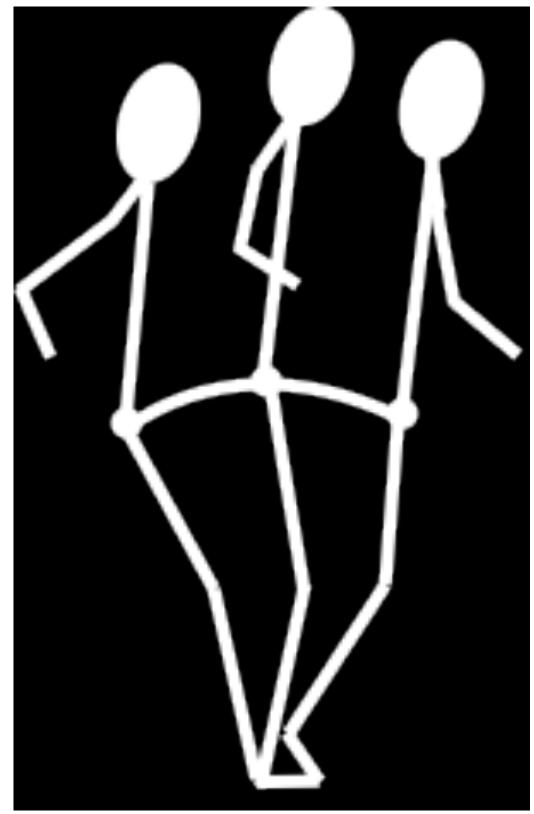
v_x increases
r_y decreases





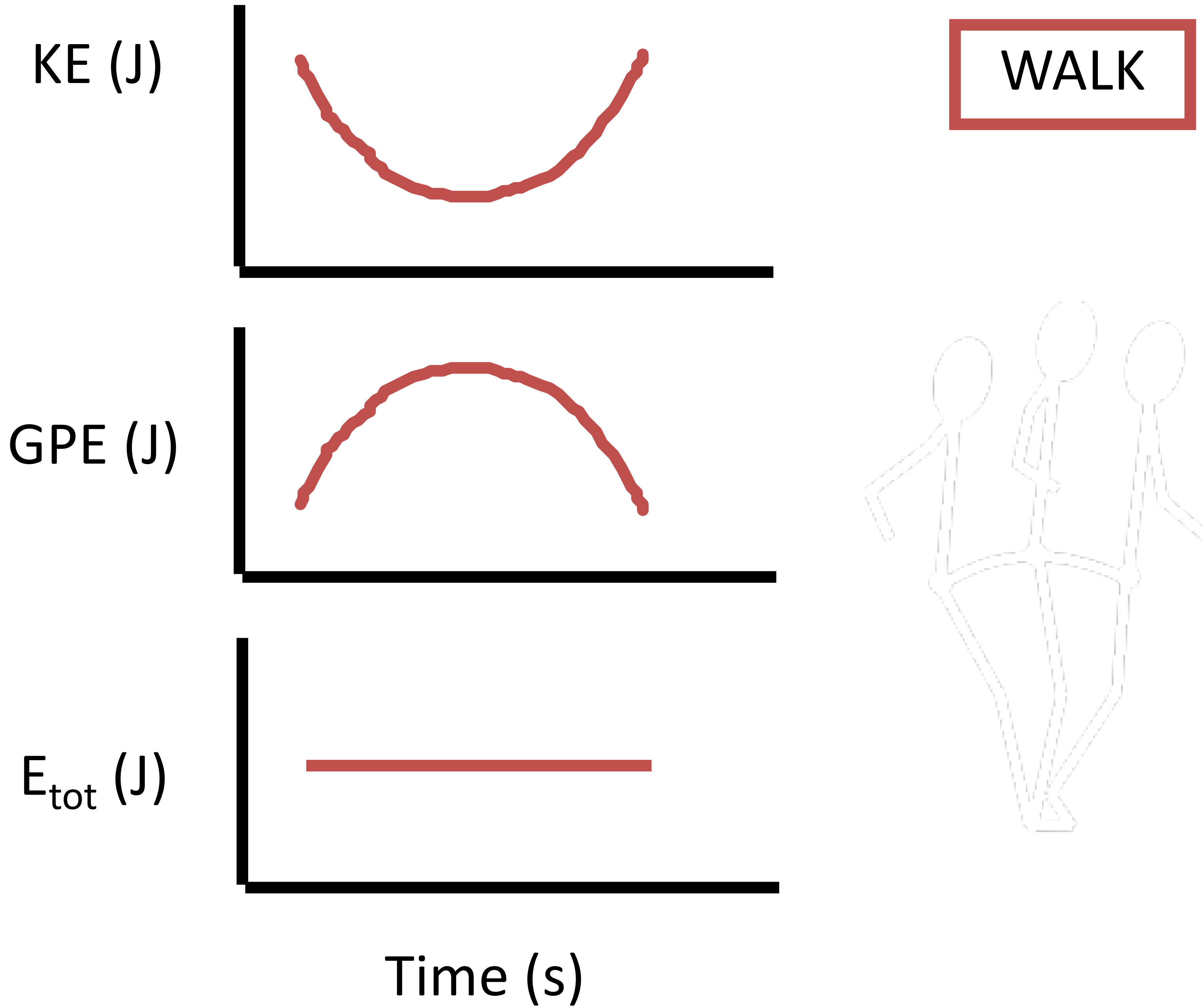
100
50
0
-50
Kinetic energy of C.O.G. (J)
100
Right stance
Left stance
50
0
-50
Gravitational potential energy of C.O.G. (J)
0
0.4
0.8
1.2
Time (s)

WALK



Walk: inverted pendulum

- 1st half of stance: decrease v_x & increase r_y
  - KE converted to PE
- 2nd half of stance: increase v_x & decrease r_y
  - GPE converted to KE
- KE & GPE “out of phase”
- Energy exchange: as much as 95%recovered during single stance phase

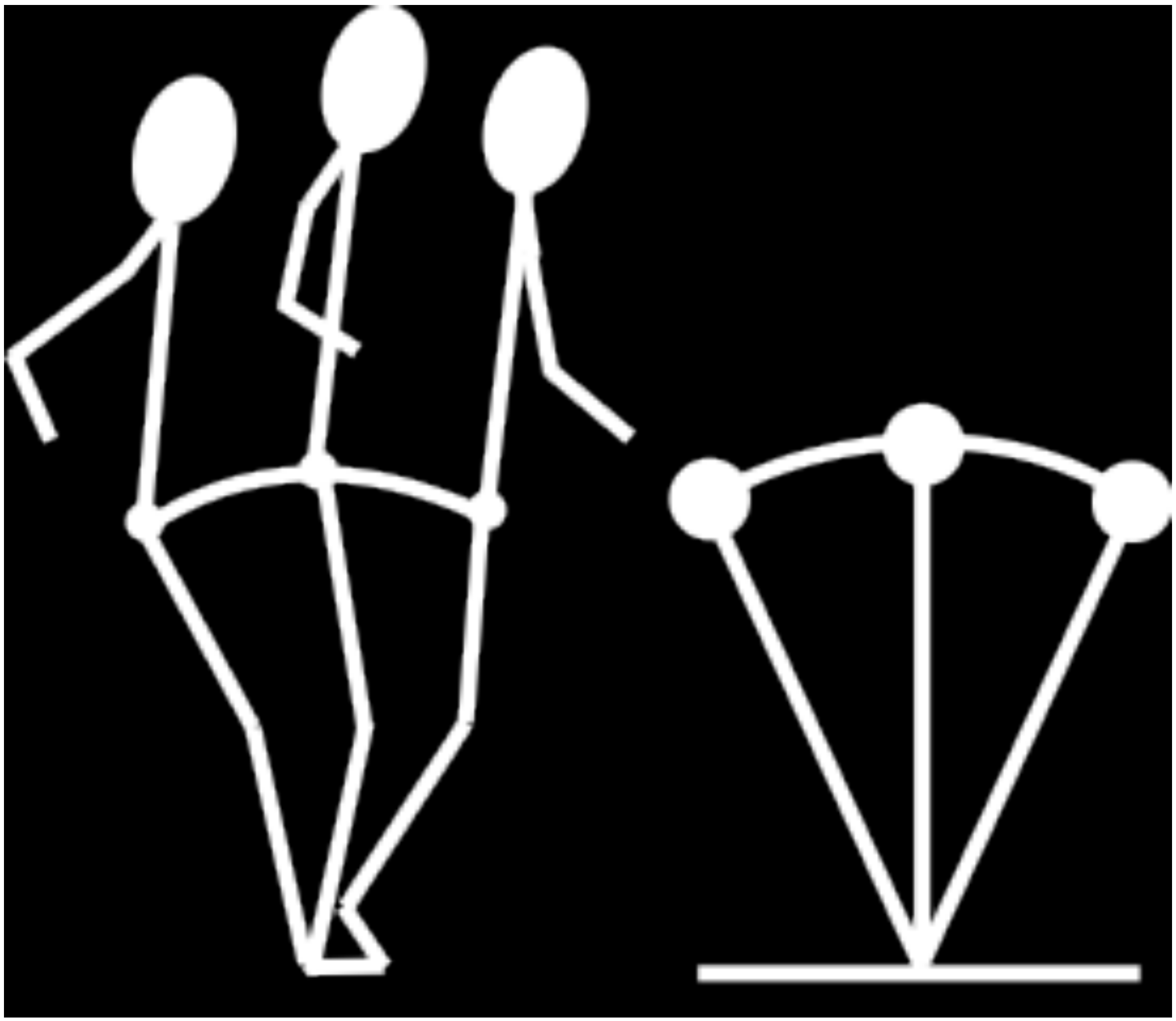


KE (J)
GPE (J)
E_{tot} (J)
Time (s)
WALK

Walk: inverted pendulum

- 1st half of stance: decrease v_x & increase r_y
  - $E_{k,t}$ converted to $E_{p,g}$
- 2nd half of stance: increase v_x & decrease r_y
  - $E_{p,g}$ converted to $E_{k,t}$
- KE & GPE "out of phase"
- Energy exchange: as much as 95%recovered during single stance phase
- But, energy is lost with each step as collision

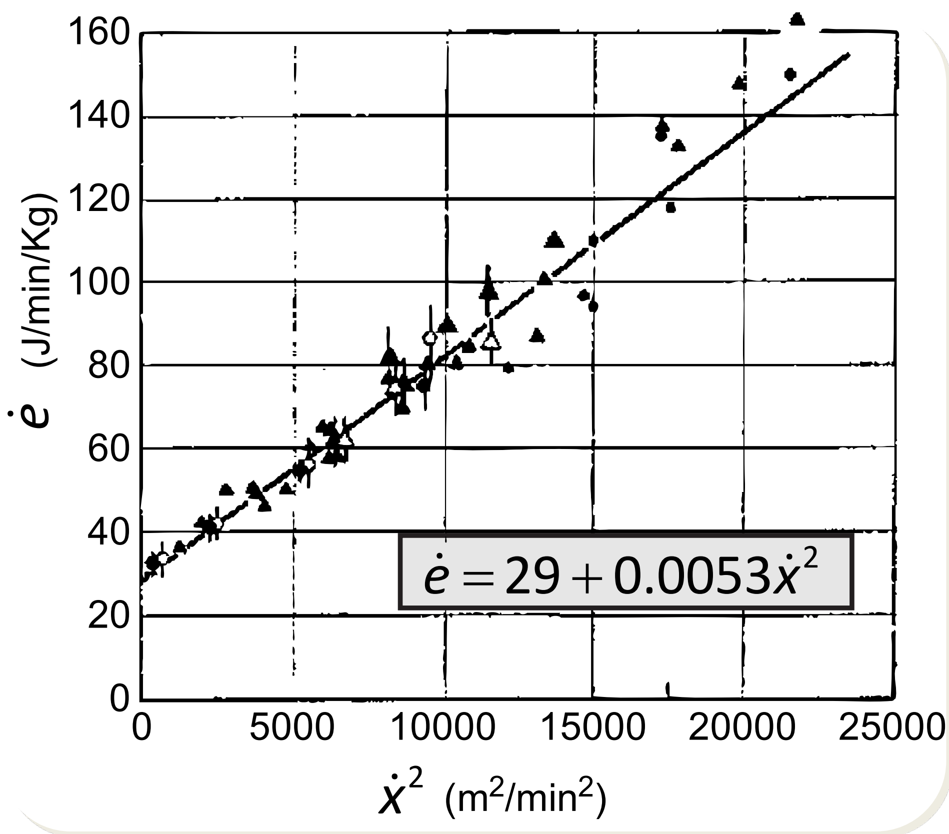
Inverted pendulum model for walking

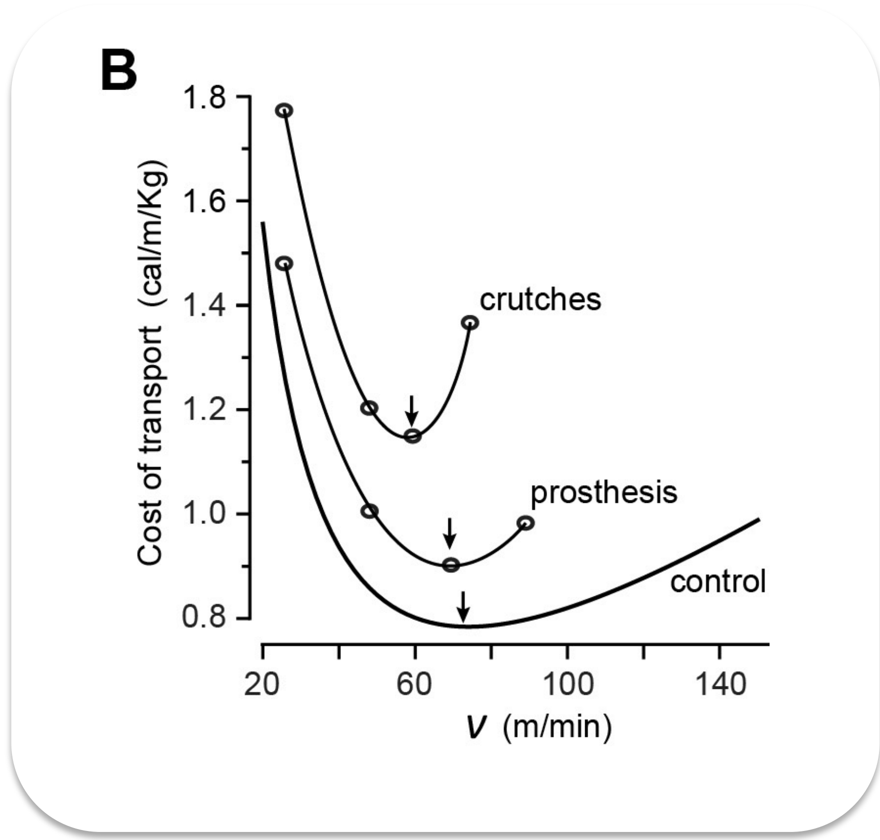


C.O.M.

Leg

Preferred walking speed and energetics





Ralston (1958)