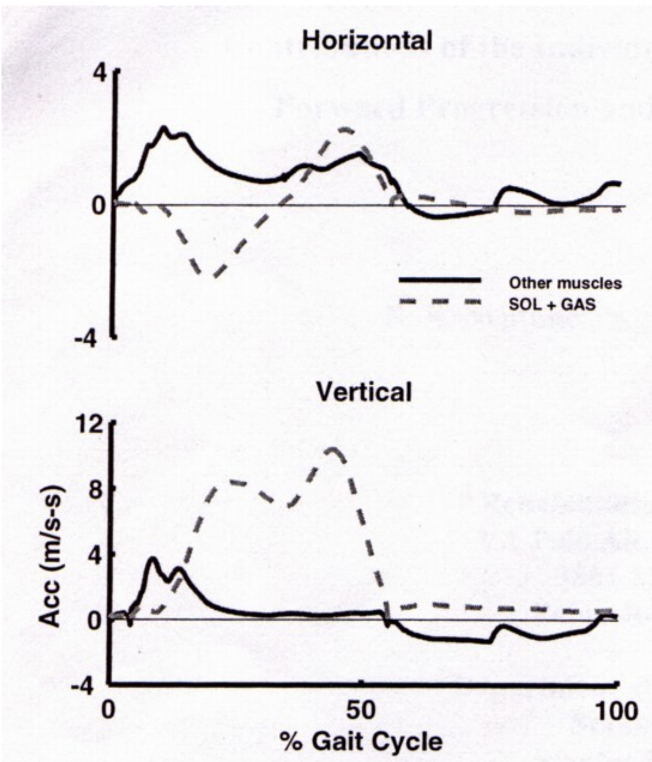
Current issues regarding induced acceleration analysis of walking using the integration method to decompose the GRF

George Chen

May 17, 2002

Stanford Neuromuscular
Biomechanics Lab Group

Muscle contribution to “forward progression”



- Task requirements for walking (Neptune, et. al, 2001)
  - Trunk support: Trunk vertical acceleration
  - Forward progression: Trunk forward acceleration
- How can muscles accelerate the trunk forward so much during early stance in steady state walking?
- Progression -> acceleration???

Induced accelerations and powers

- Induced acceleration analysis
  - In model, all set forces to zero, except force of interest
  - Determine linear/angular segment/joint accelerations
  - Repeat for each force in model - superposition
- Segment power analysis
  - Induced segment power calculated using induced linear and angular segment accelerations
  - If segment is accelerated in direction of the simulated motion, power is generated to segment

Ground Interaction / GRF Decomposition

- Hard constraints
  - Pin joint at center of pressure
  - Weld joint
- Hard constraints with inertial terms
- Integration method
- Taylor expansion (near future)

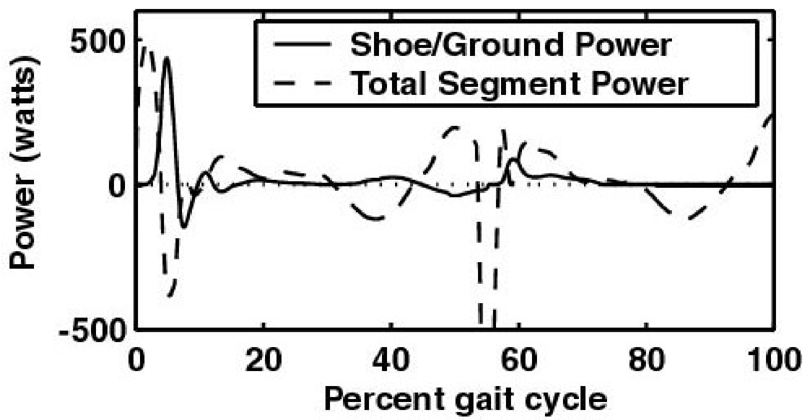
Technique: Integration Method

- To find contributed GRF attributed to a force (i.e., muscle, passive, or gravity) at time step i
  - At time step i-1, equations of motion are integrated forward over time step i-1 to i without the force of interest
  - GRF is recomputed for new system state.
  - Contributed GRF is difference between original and new GRF
- Need to choose appropriate integration time
- Velocity contribution cannot be calculated

Checks on induced acceleration results

- Superposition check
  - Net induced accelerations / powers from muscles, passive forces, gravity, and velocity = simulated accelerations / powers
  - Solution not unique
- Energy balance
  - For each muscle: Net induced powers = musculotendon power
  - Unique? No

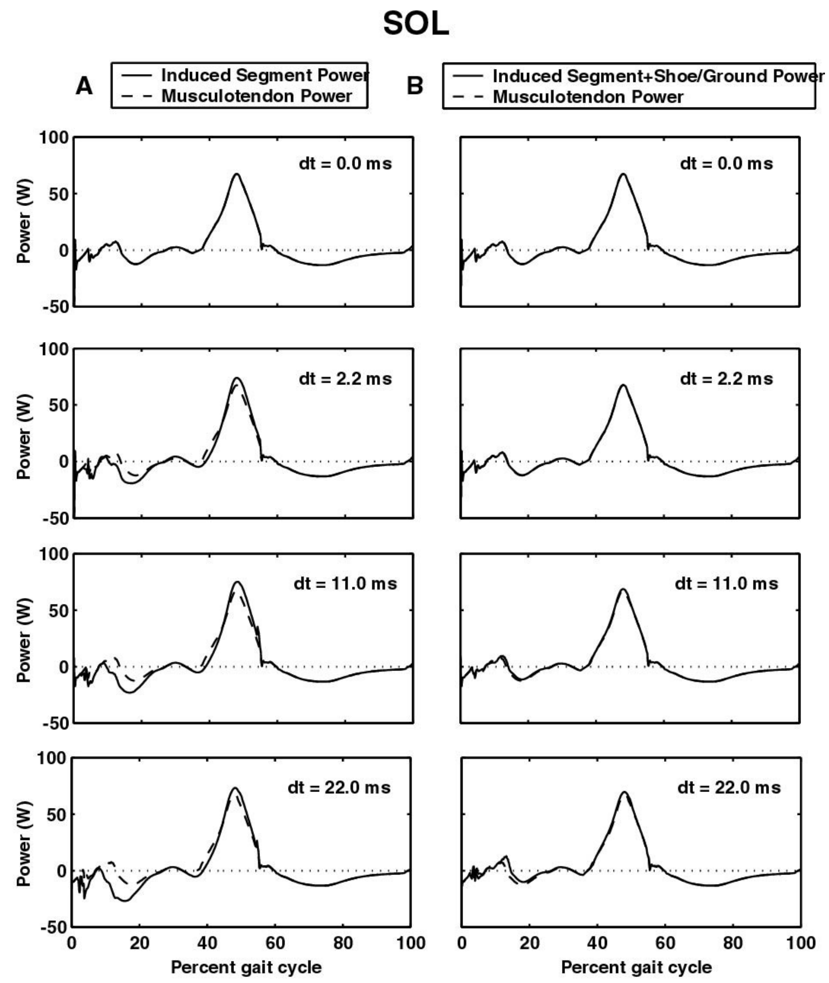
Energy balance



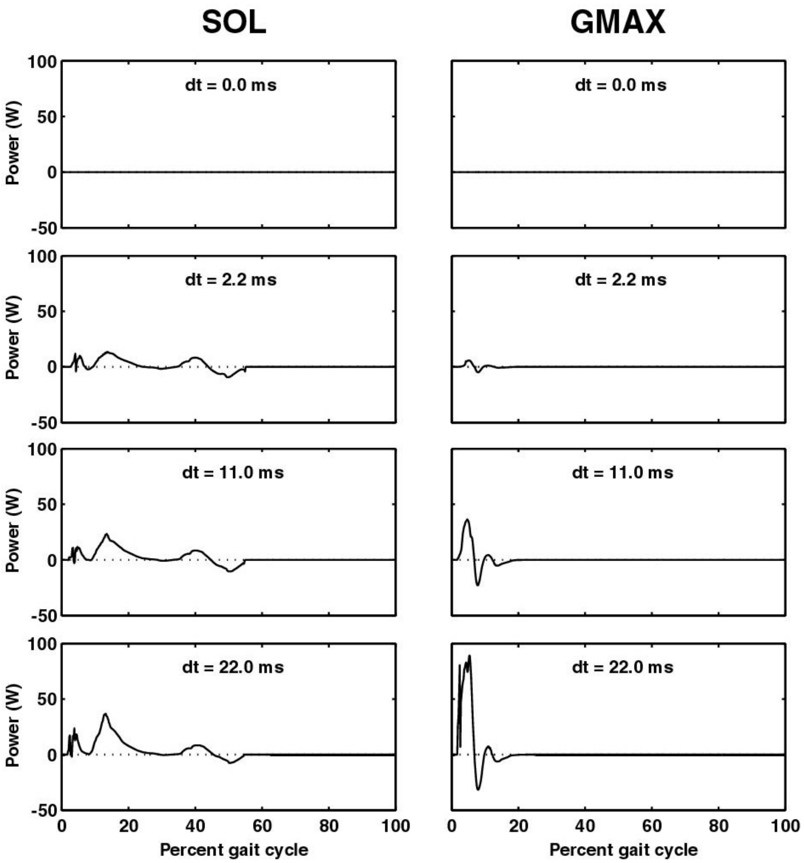
- Musculotendon power = induced segment power + induced shoe-ground power
- Shoe-ground power (GRF multipled by compression velocity of shoe-ground element) has been neglected
- Power loss / exchange to the shoe-ground is large during early stance

Energy balance using different integration step sizes

- Differences between musculotendon and segment powers increase with integration step size
- Differences are negligible when induced shoe-ground powers are included
- Neptune et al. used an integration step size of 2.2 ms, but other sizes satisfy energy balance equally well



Induced shoe-ground powers with different integration step sizes



- Muscles contribute more to GRF (and therefore, shoe-ground powers) at larger integration step sizes
- Temporal development of contributed GRF (later discussion)

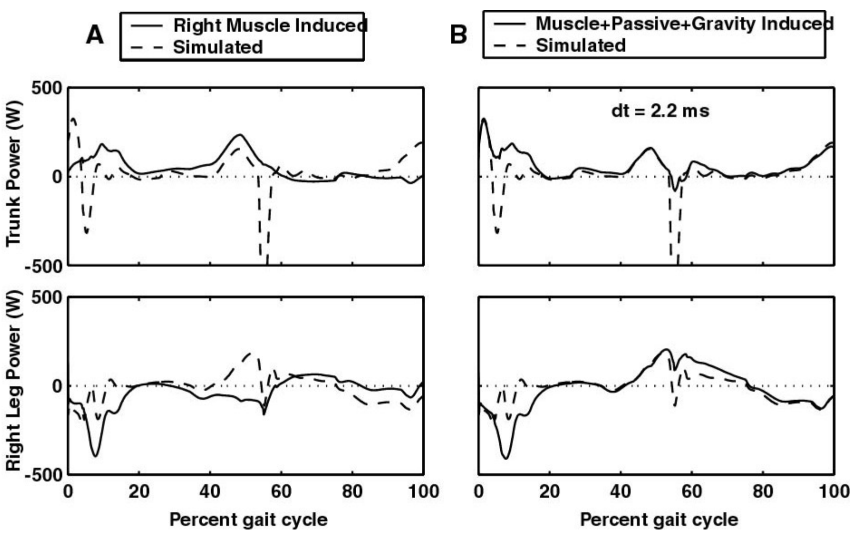
Does an energy balance imply superposition?

"If the powers add up, the accelerations must add up"

- Only if the power check is a superposition check
- Got to keep straight on what's being added up!

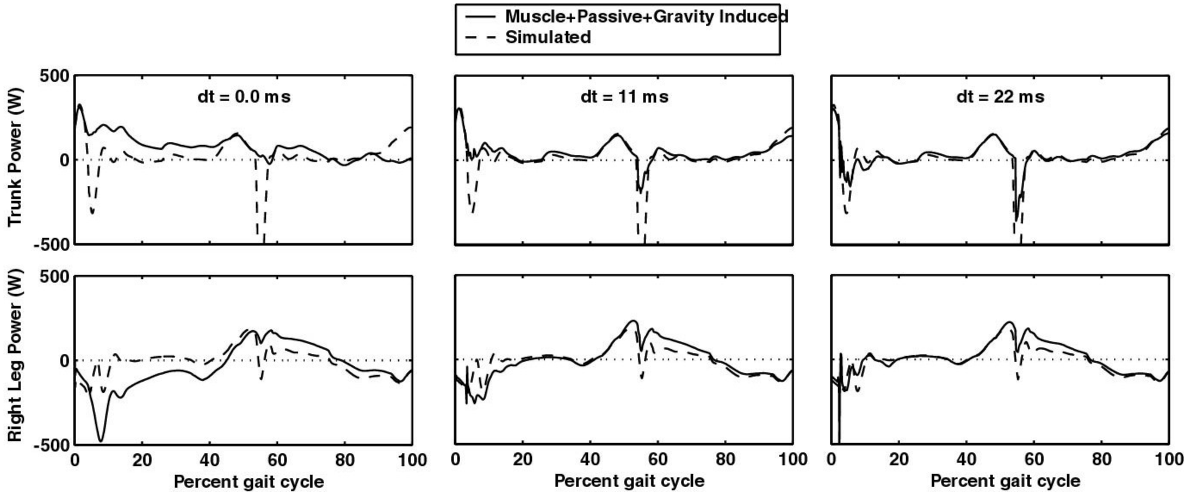
- Even if energy balance is satisfied for each muscle, the power can be distributed to the wrong segments (ex., trunk vs. right leg) and/or wrong components (ex., horizontal power vs. rotational) such that induced powers are kinematically inconsistent with simulation

Trunk and leg powers during early stance



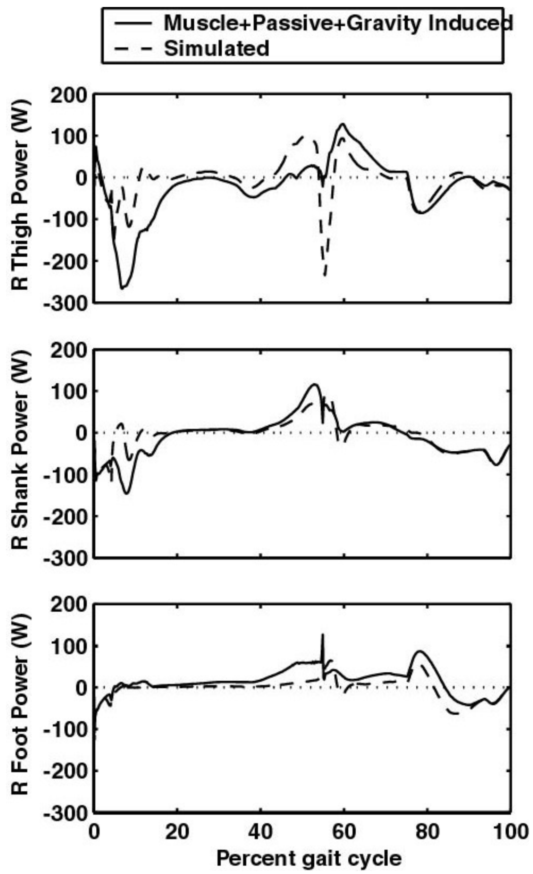
- Integration step size = 2.2 ms
- Stance leg muscles generate too much power to trunk (accelerating it forward) and absorb too much power from leg during early stance
- Difference attributed to velocity (but this assumes superposition!)

Distribution of trunk and leg power using different integration step sizes



- Velocity can’t be arbitrarily assumed to account for any difference between induced and simulated powers
- Ex., for step size = 0.0 ms, large difference between induced and simulated powers is due to not applying the GRF, but all of the GRF can’t be attributed to velocity
- Superposition doesn’t hold. Velocity is not a boundless fudge factor.

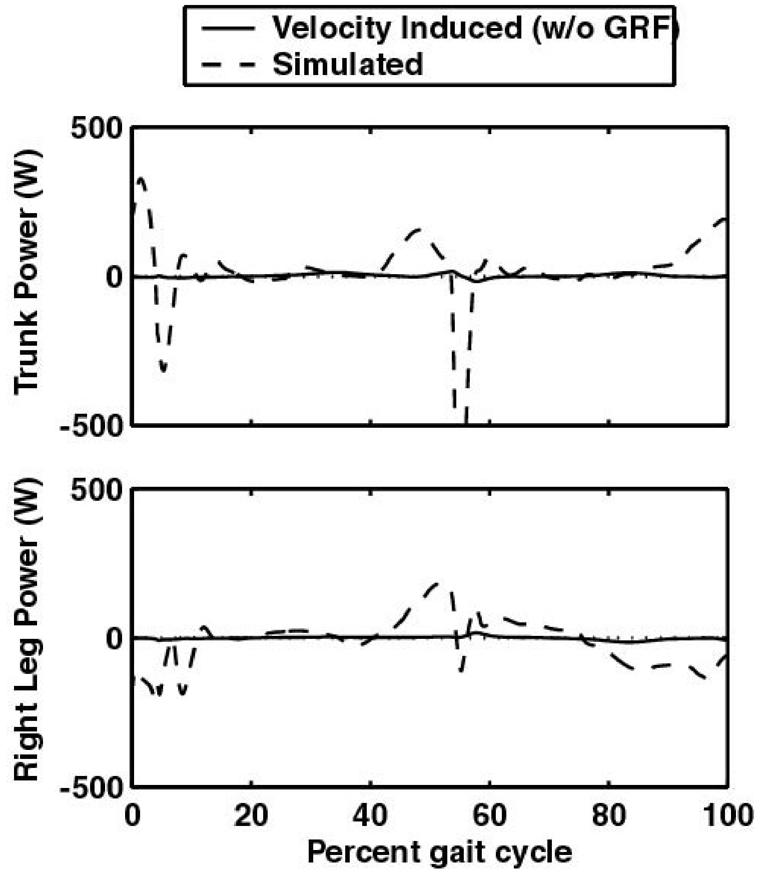
Induced thigh, shank, and foot powers



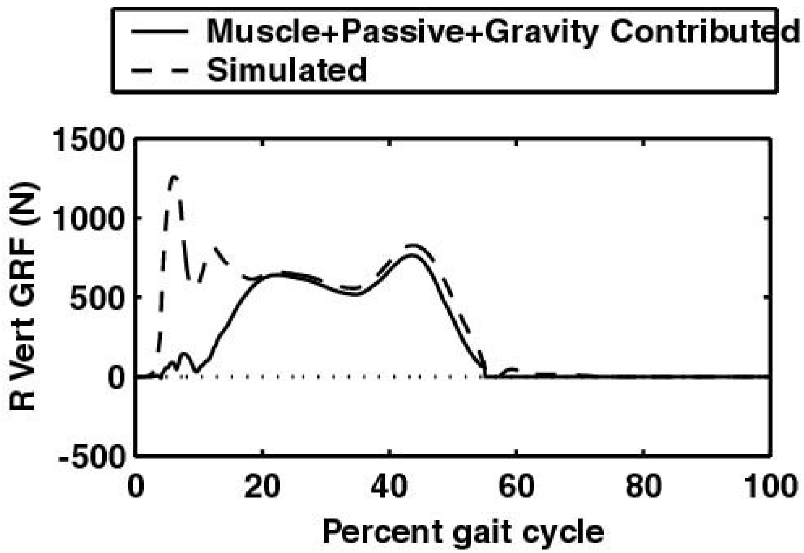
- When the leg power is decomposed into thigh, shank, and foot powers, induced powers differ from simulated throughout stance (not just during early stance)
- Muscle-induced powers distributed incorrectly even though energy balance holds

Coriolis / Centripetal contribution

- Segment power induced by coriolis / centripetal forces (w/o motion dependent GRFs) are small and can’t account for the power discrepancy during early stance
- In fact, coriolis contributions are larger during swing

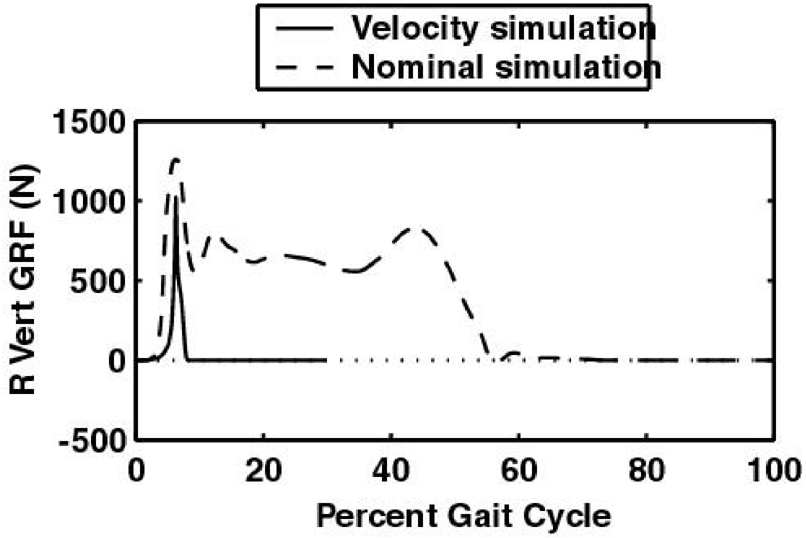


Acceleration / power contribution from motion-dependent GRFs



- Cannot be determined using integration method
- Inferred to be large, especially during first 20% of gait cycle when simulated vertical GRF is mostly unaccounted for
- Suspicious: Contributed GRF remains close to zero until plantarflexors support the body

Simulated vertical GRF with only velocity at impact



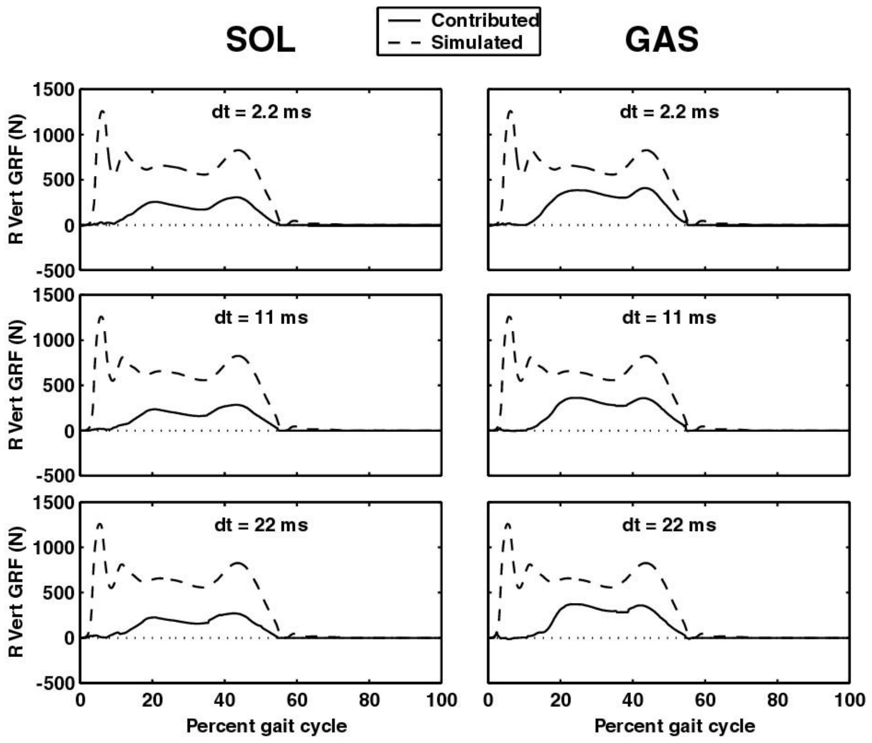
- To approximate motion-dependent GRFs, we set muscle, passive, and gravity forces to zero at heel impact and ran simulation forward
- Resulted in a GRF short spike, but not all of the GRF

Temporal development of contributed GRFs and implications

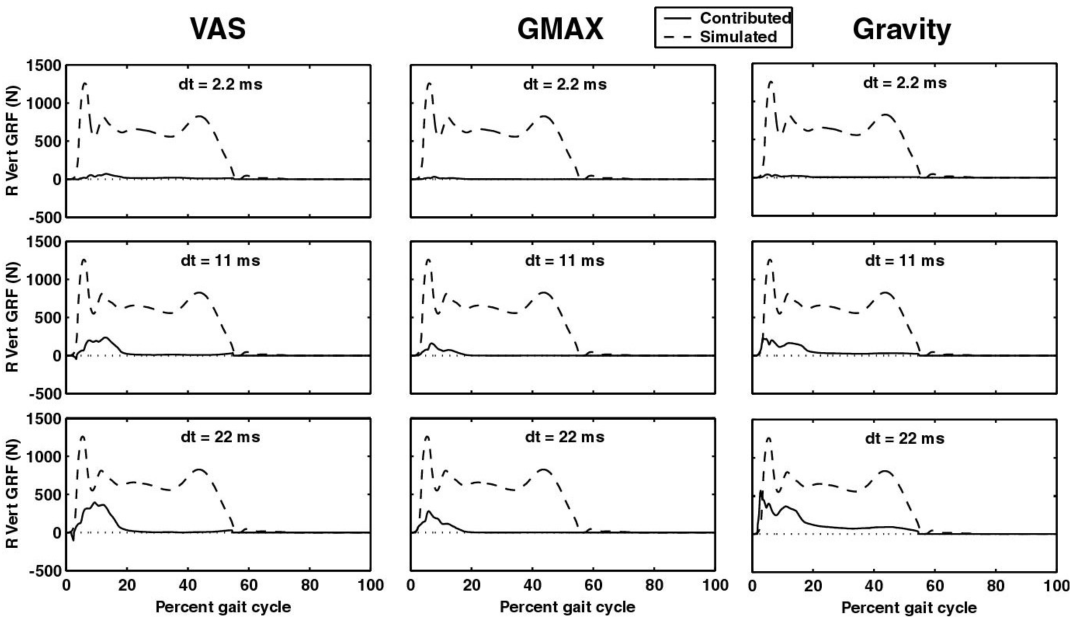
- Current interpretation of muscle function
  - Instantaneous action + action of it's contribution to the history-dependent GRF during previous 2.2 ms
- In order for contributed GRFs to develop, foot position and velocity must change
  - GAS and SOL act directly on the foot, so GRF develops fast
  - Proximal muscle and gravity act more slowly on the foot, and 2.2 ms may not capture their contributed GRF

Contributed vertical GRF of SOL and GAS using different integration step sizes

- Contributed GRF do not change appreciably from dt = 2.2 ms to 22.0 ms
- Shoe-ground elements equilibrated by 2.2 ms



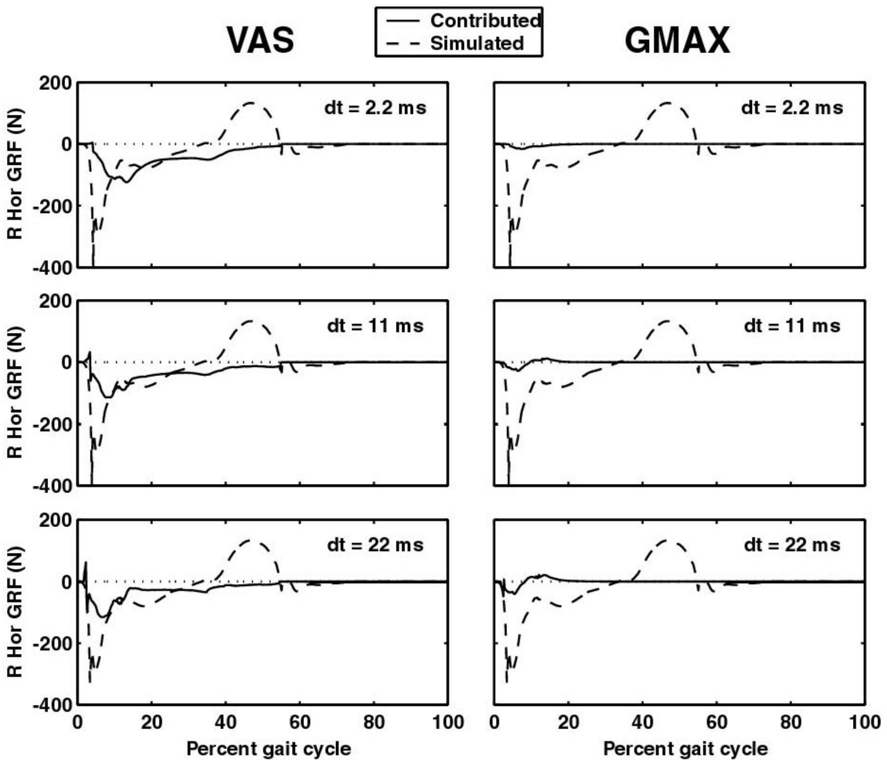
Contributed vertical GRF of VAS, GMAX, and gravity using different integration step sizes



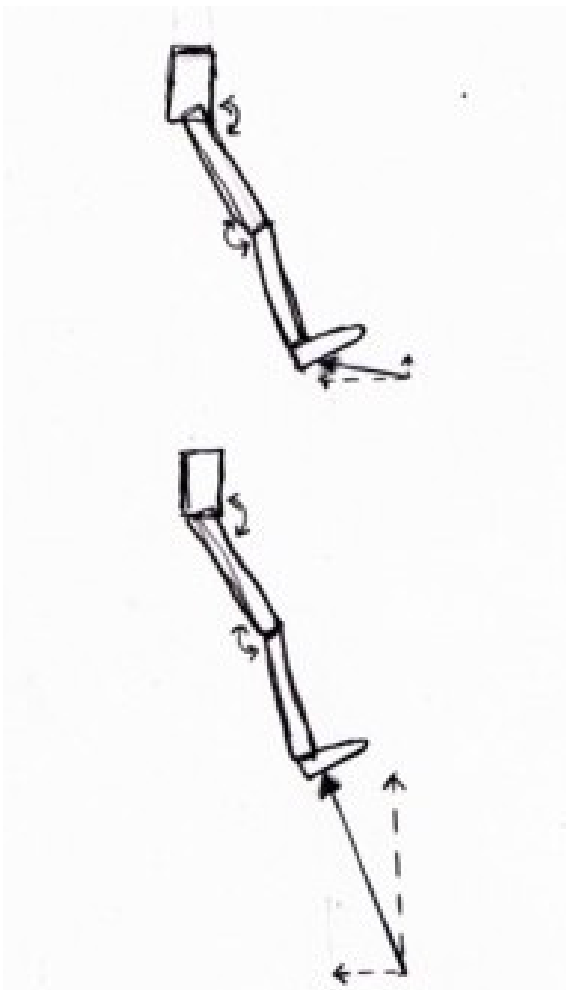
- Contributed GRF increases from dt = 2.2 ms to 22.0 ms
- Shoe-ground elements have not equilibrated by 2.2 ms
- Only a small fraction of contributed GRF is captured (-> missing GRF during early stance)

Contributed horizontal GRF from VAS and GMAX using different integration step sizes

- Interesting, contributed horizontal GRF do not increase as appreciably from dt = 2.2 to 22.0 ms
- "Coulomb" friction model reacts more quickly
- However, questionable whether horizontal GRF can equilibrate, since friction model lacks a velocity-independent term



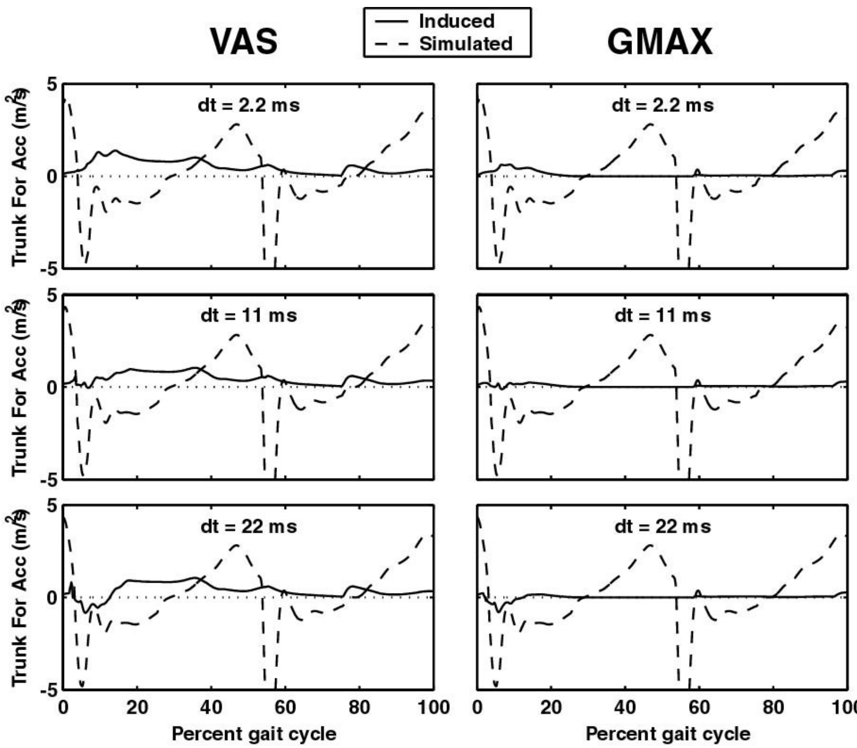
Implications to trunk support and forward progression from VAS and GMAX



- dt = 2.2 ms
  - Limited trunk support (muscles push leg into ground)
  - GRF brake primarily the leg
  - Muscular component accelerate trunk forward
- dt = 11.0 or 22.0 ms
  - Trunk and body support (legs push off ground)
  - GRF brake both leg and trunk
  - Net action can be neutral or braking

Induced trunk forward progression (acceleration) using different integration steps

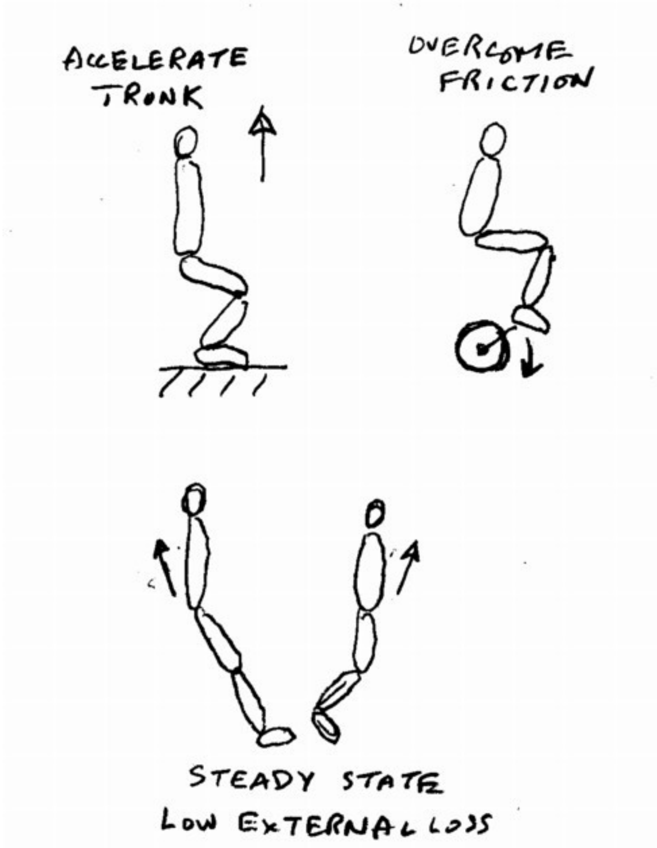
- The forward trunk acceleration induced by VAS and GMAX during early stance results in the power discrepancy discussed previously
- Decceleration of the trunk by VAS and GMAX results in a more reasonable superposition



Glaringly suspect?

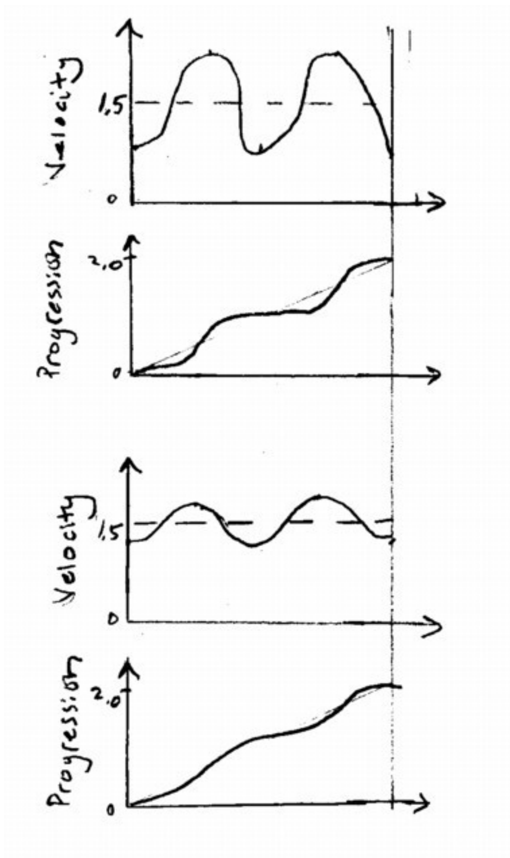
- Muscles accelerate the trunk forward during early stance, even though GRF is directed backward and trunk slows down
- Result has been presented to audience members and reviewers. Why is it not questioned?
  - Perhaps, confusing terminology. In walking, forward progression is commonly considered to be forward displacement of trunk
- During early stance, the trunk progresses forward, but it is not accelerated forward

Does forward acceleration define a task requirement for walking?



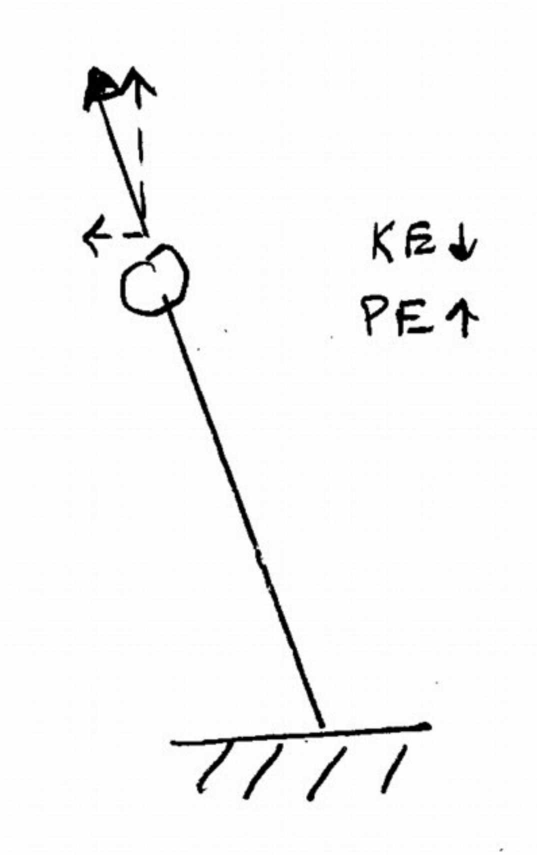
- Maximum height jumping
  - Accelerate the trunk to achieve maximum energy at take off
- Pedaling
  - Accelerate crank to overcome frictional forces
- Walking
  - Trunk energy is steady state over a gait cycle
  - Not a lot of external loss from friction / damping

Average forward acceleration of trunk is zero in steady state walking



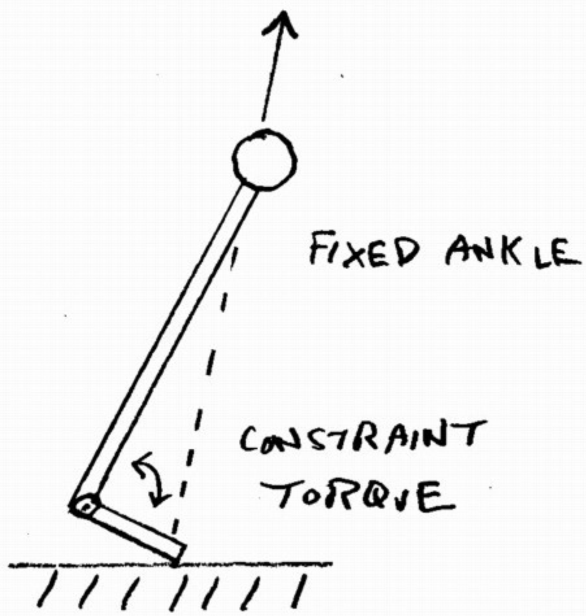
- Average forward acceleration is zero, regardless of walking speed and even direction
- Magnitude of forward acceleration related to velocity fluctuation during gait cycle (not a task requirement)
- Momentum progresses trunk -- Balance of acceleration maintains the momentum to next gait cycle

Horizontal trunk energy loss



- If horizontal energy loss was dissipative and unavoidable -> Rationale to use acceleration
- Source of loss
  - Transfer to potential energy of gravity (probably dominates in normal gait)
  - Absorption by muscle and passive joint torques (could dominate in dysfunctional gait)
  - External loss to friction / damping (relatively small)

More appropriate definition of task requirements for walking?

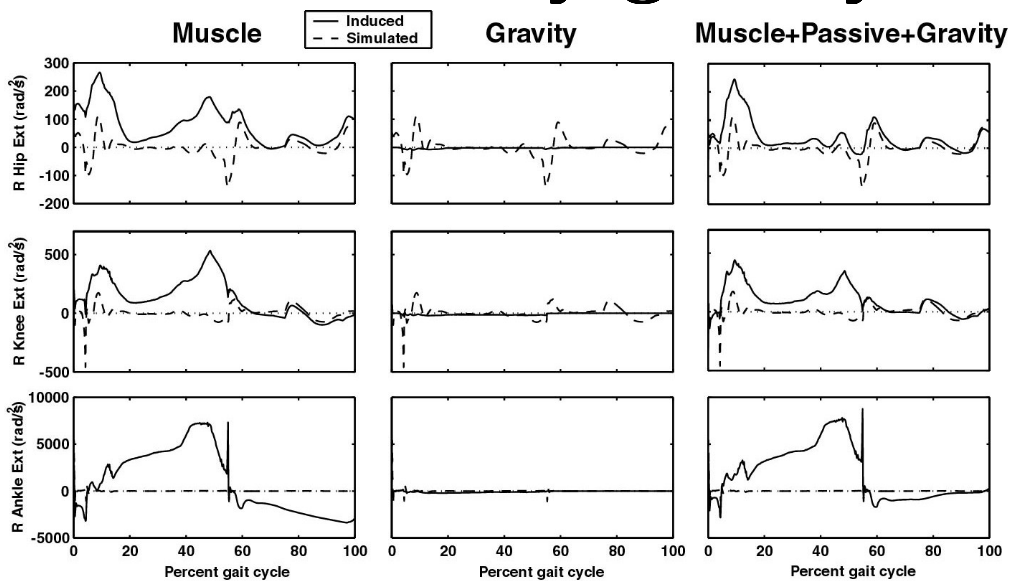


- Inverted pendulum model
  - Accelerate trunk perpendicular to velocity
  - Definition encompasses both trunk support and forward acceleration
- Muscles accelerating the trunk forward is not inconsistent with controlled-roll off
  - Ex., Constraint torque of fixed ankle accelerates trunk forward if analyzed as a joint
  - Muscles can the stiffen the leg, such that it acts like a pendulum

Future discussion

- Can induced acceleration analyses be used to understand gait abnormalities such as slow speed, crouched stance, decreased knee flexion during swing, and other state parameters related to positions and velocities?
  - Related to Felix’s talk, but let’s look at some conceptual examples from gait

Lack of sufficient joint angular flexion induced by gravity



- Muscles support the trunk by accelerating the joints strongly into extension
- Gravity accelerates body downward, essentially as a unit
- Results in an imbalance of joint extension acceleration throughout stance