The challenge of deducing meaningful results from induced acceleration analyses

George Chen

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Honda Fundamental Research Lab

Induced acceleration analysis

- Regarded as a powerful tool in the interpretation of muscle function during a motor task
- Using a dynamic model, technique decomposes net accelerations into components induced by individual forces (i.e., joint torques, muscle forces, gravity, etc.).
- Important, because muscles can accelerate joints and segments that they don’t span through their effect on intersegmental forces throughout body

Computing induced accelerations

- Equations of motion

$$\ddot{q} = I^{-1}(q)[R(q)F^{mus} + G(q)g + V(q,\dot{q}) + F^{non}(q,\dot{q})]$$

$q, \dot{q}, \ddot{q} =$ vector of generalized coordinates, velocities and accelerations

$\mathrm{I(q)} =$ system mass matrix (NON - DIAGONAL)

$\mathrm{R(q)} =$ moment arm matrix

$\mathrm{F^{mus}} =$ vector of muscle forces

$\mathrm{G(q)g, V(q,\dot{q}), F^{non}}(q,\dot{q}) =$ vector of gravity, coriolis/centripetal, and non - muscles terms.

- Acceleration induced by a force of interest
  - Set all forces to zero, except for force of interest
  - Determine linear/angular segment/joint accelerations
  - Repeat for each force in model

Applications

- Induced acceleration has been used to study
  - Balance in standing
  - Crank propulsion in pedaling
  - Trunk support / propulsion, limb acceleration in walking
- However, results from induced acceleration analyses are often non-intuitive, and their physical meaning has generated much debate

Common reasons why induced acceleration results are non-intuitive

1. Difficulty in visualizing effect of induced intersegmental forces throughout body (good reason for IA analysis)
2. Inappropriate GRF decomposition (ex., VAS during early stance)
3. Confusion between induced accelerations with force's effect on velocity or position states (ex., misleading terminology hasn't helped: forward progression -> acceleration)
4. IA results describe effect of isolated forces on linkage system with all joints free. Most people think of muscle function (or what other forces do) in the context of certain joints being nearly locked (many examples)

If (2), (3), or (4) -> Important to understand why results are non-intuitive

– In determining clinical significance of result
– In explaining to scientific community how IA results fit in with intuition gained from other concepts and types of analyses

Presentation Outline

- Examples
  - Non-seated pedaling: Potential muscle contribution to trunk support and crank acceleration
  - Kicking: A strategy to maximize foot speed at impact
  - Musculoskeletal walking model: Interpretation of stance leg muscle and TA “contribution” to knee flexion

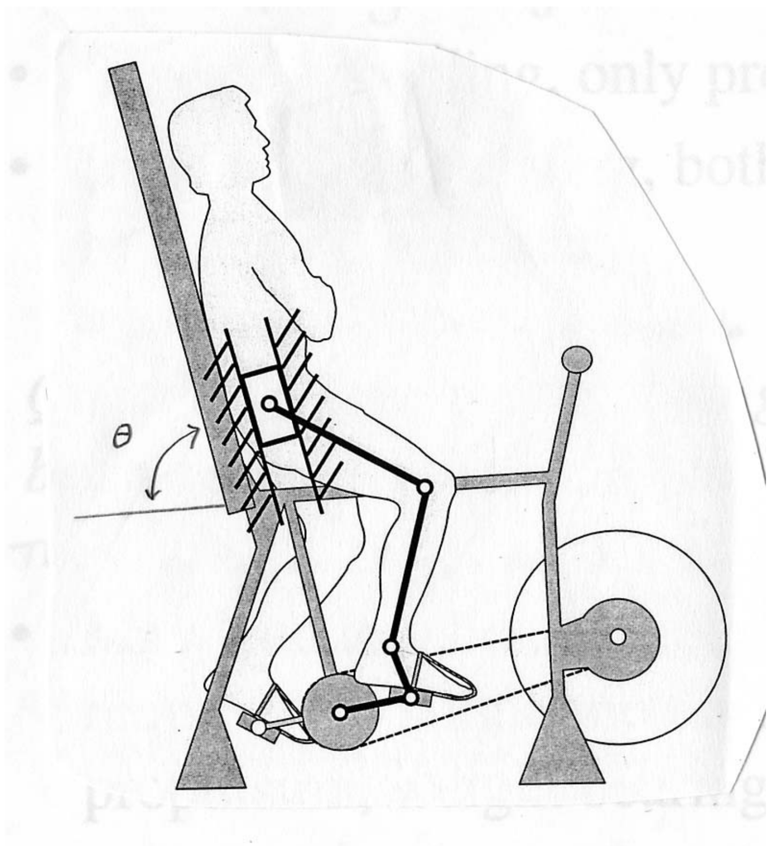
Presentation Outline (continued)

- Discussion
  - Model sensitivity. Are differences in interpretation meaningful?
  - Limitation of instantaneous analysis. Can we gain insight on how forces affect position and velocity states in task?
  - Reconciliation:
    - “Targeted” model simplification.
    - Combining IA results with mechanical intuition, perturbation experiments, joint torque analyses, etc.
  - Back to basics: What are induced accelerations? “Contribution” or potential effect?

Examples

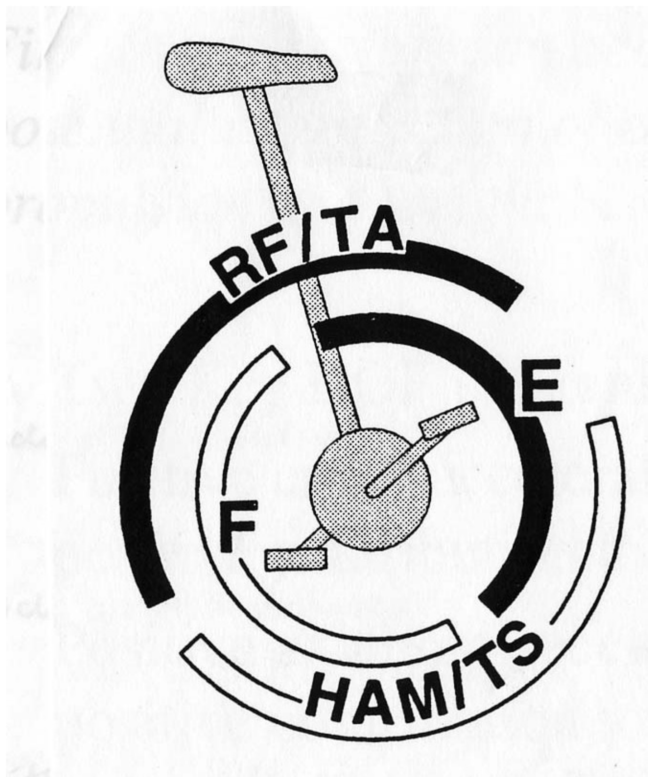
Non-seated pedaling

- Weight-bearing pedaling task
- Hip free to slide on backboard - 4 DOFs
- Requires both trunk support and crank propulsion
- Task requirements are well-defined in terms “accelerations”

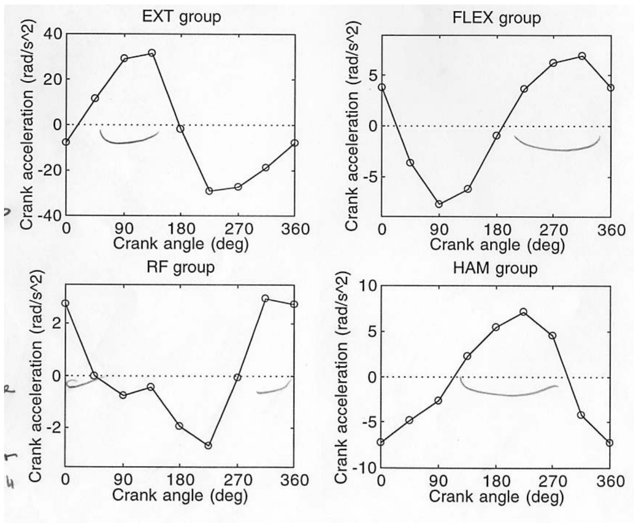


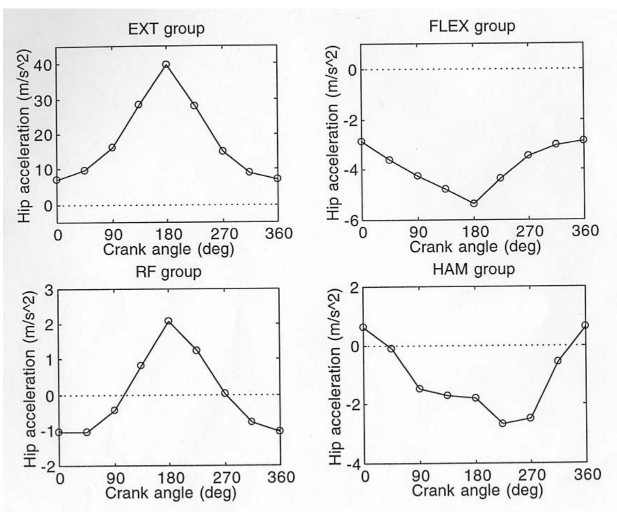
Induced acceleration analysis using functional muscle groups

- Musculoskeletal pedaling model (Raasch)
- Six functional muscle groups
- Axial trunk and forward crank acceleration: Potential contribution of EXT, FLEX, RF, and HAM muscle groups
- Ankles assumed locked by TA/TS muscle groups (!)



Trunk and crank induced acceleration results





- Maximum isometric muscle forces applied at various points in pedal cycle
- Crank acceleration results
  - Muscle groups accelerated crank forward at times consistent with excitation pattern in seated pedaling (Strategy need not change from seated pedaling)
- Trunk acceleration results
  - Only EXT muscle group could strongly accelerate the trunk axially for support

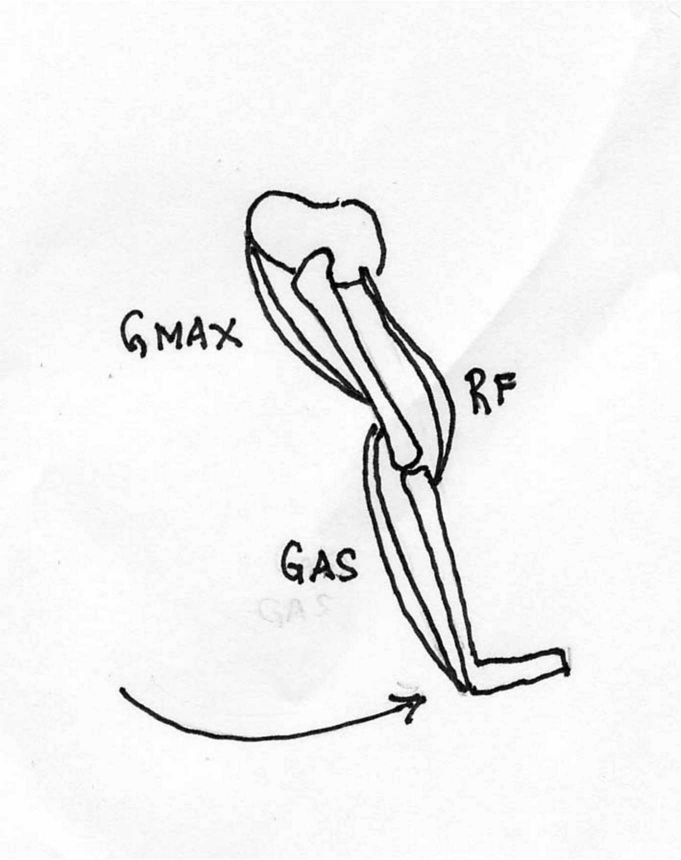
Non-seated pedaling control strategy

- From the muscle groups' potential contribution to crank and trunk acceleration -> hypothesize non-seated pedaling strategy
  - Two extensor bursts (downstroke and upstroke), with bigger burst during downstroke to maintain crank propulsion
  - RF and HAM active during upstroke/downstrike transitions as in seated pedaling
  - Hypothesized strategy agreed with EMG data collected in humans

If a more complete pedaling model was used…

- With ankles unlocked, plantarflexors are strongest potential contributor to trunk support and crank acceleration, since they transfer forces to the crank
- Are results generated with locked ankles invalid because model was simplified? Results seemed useful, nonetheless.
- Could we have come to the same conclusion about proximal muscle control using a model with ankles unlocked?
  – Yes, but not as easily. Can piece together -> Plantarflexors can accelerate the crank for a short period of time, but ankle would quickly go out of range. Proximal EXT muscles can extend hip and knee, dorsiflex the ankle, and allow crank acceleration to continue…

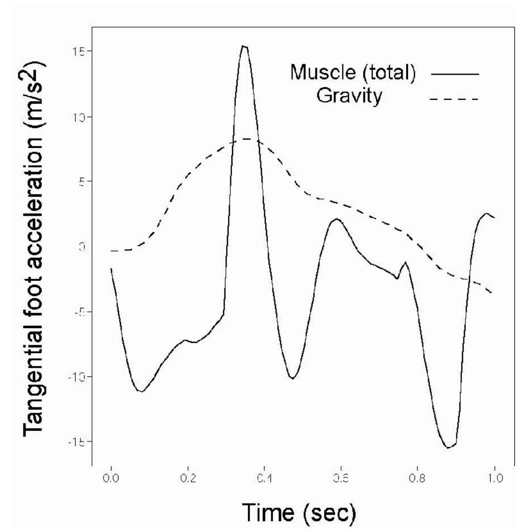
Kicking model

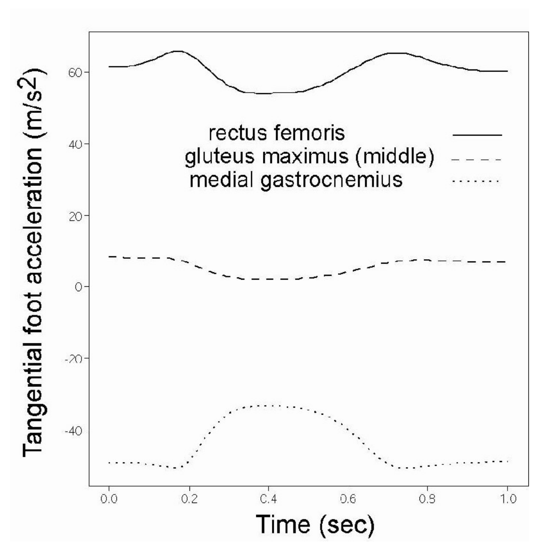


- Pelvis, thigh, shank, and foot model in SIMM
- Pelvis position and ankle joint angle locked (!) -> 2 DOFs
- Three muscles: RF, GMAX, and GAS
- Began with nominal kicking simulation
- Goal: Develop muscle excitation strategy to maximize foot speed at impact (velocity state!)

Induced acceleration analyses

- Analysis on nominal simulation
  - Muscle contribution to tangential foot speed was negative for most of kick motion
  - Gravity accelerated foot forward after muscles raised and brought leg backward
- Analysis using max. isometric force
  - Only RF had the potential to strongly accelerate the foot forward during kicking motion





Strategy to maximize foot speed

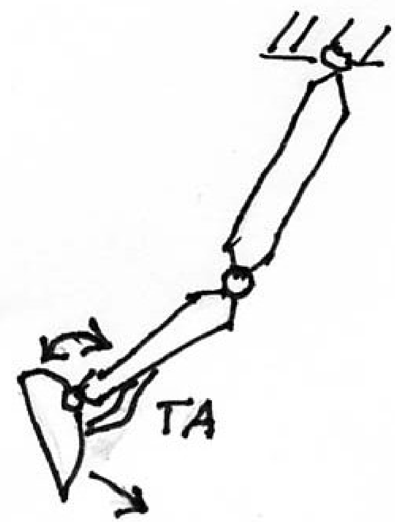
- Hypothesized strategy
  - Excite GMAX and GAS for t = 0.0 to 0.5 s to bring leg backward
  - Excite RF for t = 0.5 to 1.0 s to accelerate foot forward
- Foot speed at impact greatly increased
  - Attributed to increased contribution from both gravity and RF
- Alternative strategy of just exciting RF produced much lower foot speed at impact

Importance of combining mechanical intuition/insight with IA results

- Only RF could strongly accelerate the foot forward at any instant in the kicking motion, but GMAX and GAS had the potential to contribute to state changes that later allowed gravity to accelerate the foot
- Needed to combine instantaneous picture with mechanical intuition to obtain optimal solution

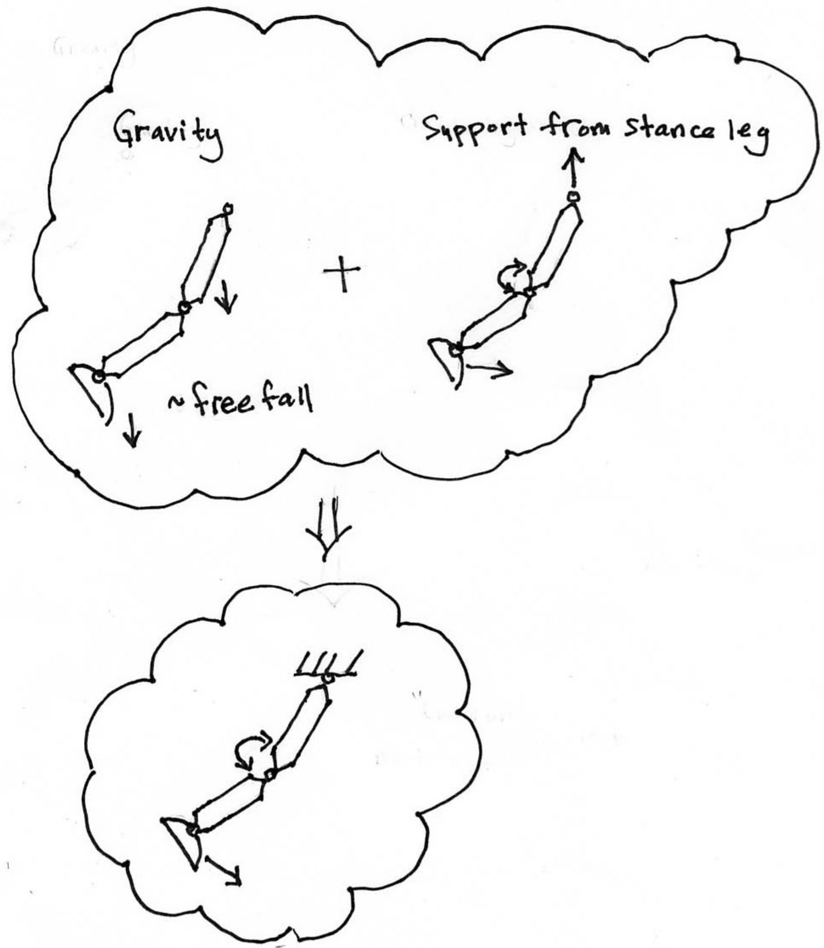
If a more complete kicking model was used…

- If ankle unlocked, TA would be strongest potential contributor to foot acceleration for much of kicking motion
  - Foot is light, and TA can accelerate the ankle into dorsiflexion very strongly
  - However, TA has limited capacity to increase foot speed, since ankle would go out of range



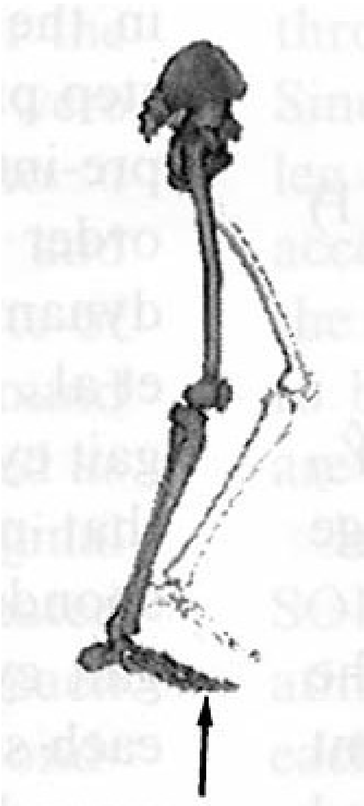
If a more complete kicking model was used… (continued)

- Without pelvic support, gravity does not swing leg forward (~ free falls)
- If stance leg muscles supported pelvis, most of foot acceleration attributed to gravity in pelvic constrained simulation would be attributed to stance leg muscles
  - However, force from stance leg muscles cannot be increased to increase foot acceleration, since only certain amount of force is needed to support trunk
- Results from simpler model seems more useful and intuitive



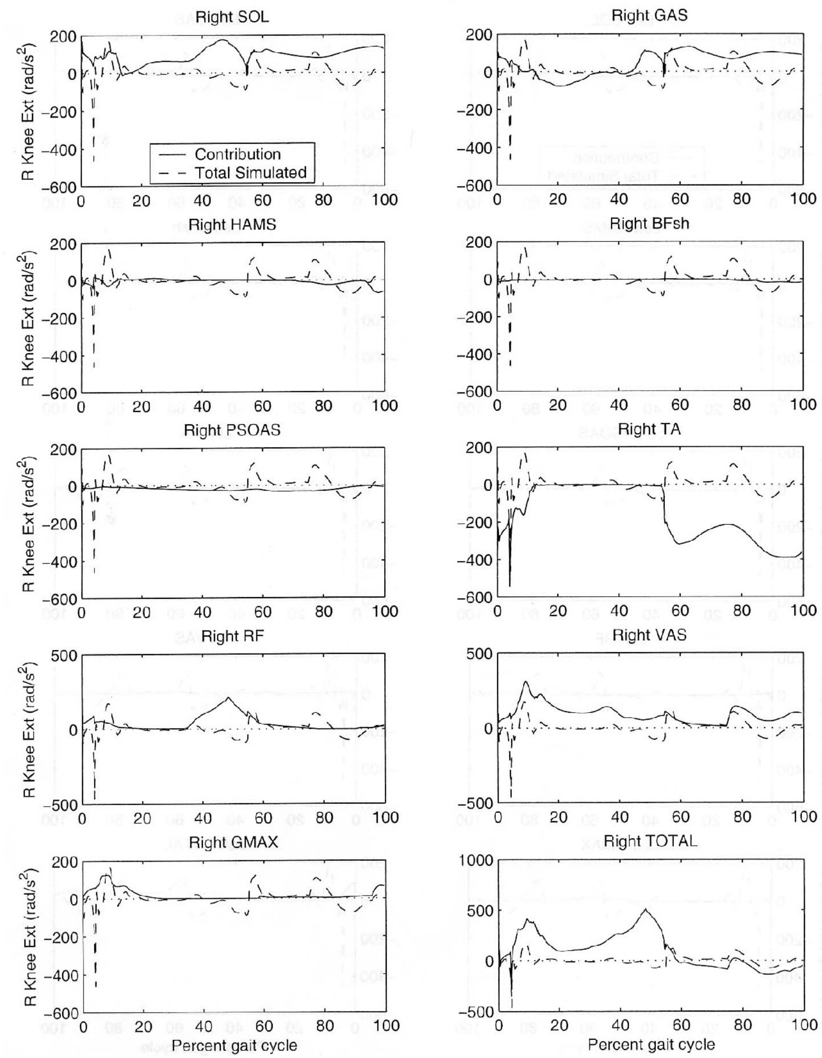
Induced swing knee flexion in musculoskeletal model of walking

- 2-D musculoskeletal simulation of walking (Neptune, et al.)
- GRF decomposed using perturbed integration (2.2 ms time window)
  - Some problems with GRF decomposition, but interpretations regarding induced swing knee flexion are insensitive



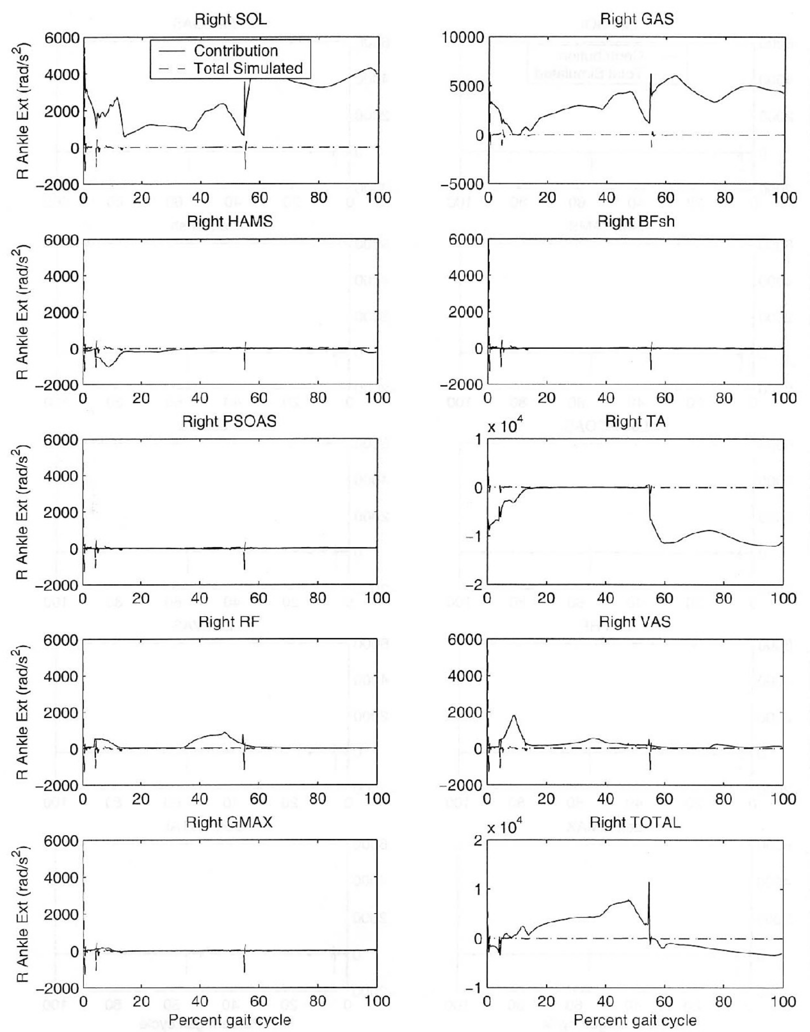
Induced swing knee acceleration from ankle muscles

- TA -> strongest contributor to knee flexion (by far!)
- GAS and SOL (together) extend knee with comparable magnitude
- How is it possible?
- Are results clinically meaningful?

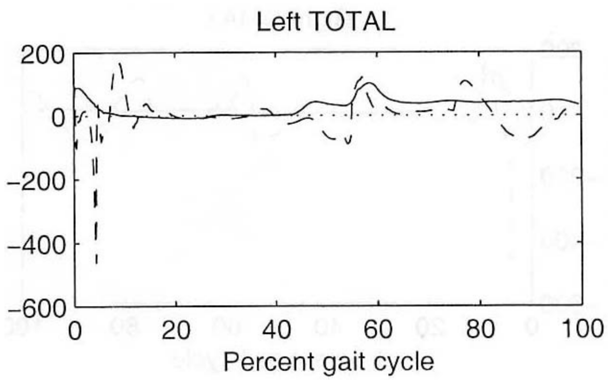


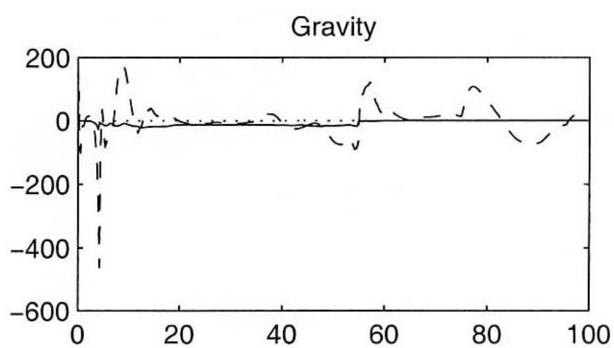
Co-contraction of ankle muscles inflate contribution to knee acceleration

- Even larger induced accelerations cancel out at the ankle
  - Ankle muscles accelerate ankle joint ~25 times more strongly than knee joint
- Clinical implication
  - Cannot increase TA excitation by itself to flex knee without causing serious acceleration imbalance at ankle



Swing knee acceleration induced by trunk support muscles





- Trunk support muscles from stance limb (i.e., plantarflexors) extend swing knee
- Gravity does not extend swing knee, since its GRF contribution is low and doesn't support the trunk
- Note: In 3-D model, hip abductors that provide frontal support would also extend swing knee

Swing limb models

- With anatomically complete model, need to account for potential state changes at ankle and trunk to assess significance of knee acceleration induced by swing limb ankle and stance limb support muscles.
- Simpler model with pelvic motion prescribed and ankles locked may isolate more meaningful results (i.e., accelerations induced by hip and knee torques of swing limb)

- Note: Co-contraction between TA and GAS can flex the knee significantly if ankle torques cancel, and knee moment from GAS flexes knee
  - Strategy requires bi-articular muscle
  - Strategy can be hypothesized using simple or complex model with different IA interpretation

Discussion

Model sensitivity: Are differences in interpretation meaningful?

- Traditional joint torque or simulation analyses
  - Model degree of freedom can be reduced by constraining joints that are essentially locked during the task without significantly affecting torques or muscle forces required at other joints to accomplish task
  - Can still learn a lot about muscle control at active joints
- Induced acceleration analyses
  - Same reduction in degree of freedom greatly affects accelerations induced by torques or muscle forces at other joints
  - Do they reflect meaningful differences in muscle “function”?

Viewpoints on model sensitivity

- Viewpoint 1: Since more complete models produce different interpretations of muscle function, the body must be modeled as realistically as possible.
  - Ultimately, one correct interpretation
  - Caveat: All of our interpretations will likely be found incorrect once we get to “Hatze” level complexity (ex. toe joint, etc.).
- Viewpoint 2: If different interpretations of muscle “function” do not reflect significant differences in muscle control, muscle forces, or joint torques required at active joints, then these differences in interpretation are not meaningful
  - Induced accelerations should not be used to define muscle “function”, except for a particular model
  - Free to choose model that gives you most meaningful insight

Mapping of results from simple to more complete models

- Pedaling
  - Accelerations induced by GMAX in ankle-locked model ~= accelerations induced by GMAX / plantarflexor synergy with ankles unlocked
- Kicking
  - Accelerations induced by gravity in pelvic-constrained model ~= accelerations induced by trunk support muscles and gravity with pelvis unconstrained
- Overall descriptions of task dynamics are similar, but the accelerations induced by individuals muscles are different (ex., GMAX accelerates leg instead of crank when ankle is included).

Limitation of instantaneous analysis

- Can we gain insight on how forces affect position and velocity states?
  - Not easily
  - Ex., TA can induce large instantaneous knee accelerations, but large non-instantaneous state changes at ankle limits TA's ability to affect knee angle by itself
- Can examine induced accelerations at all DOFs in order to assess potential non-instantaneous effects
  - However, requires much mechanical intuition

Reconciliation: Isolating more meaningful results for clinical recommendations

- “Targeted” model simplification
  - Choose the model that gives you the most physical insight into your problem
  - Eliminate DOFs that primarily transfer power between segment and/or can’t be affected much
- Consider the potential effect of non-instantaneous state changes by examining induced accelerations at all active DOFs
- Combine induced acceleration results with mechanical intuition, perturbation experiments, joint torque analyses, etc. to make clinical recommendation

“Targeted” model simplification

- “Targeted” model simplification
  - Maintains more reasonable “power flows” through segments by eliminating DOFs that primarily transfer power when active (ex., ankle joint in pedaling)
  - Isolates more meaningful interpretations by eliminating potential effects that would involve large state changes at DOFs that can’t be affected much in task (ex., trunk support in walking)
- However, results only provide insight into muscle control of active of DOFs (ex., proximal muscle control in ankle-locked pedaling model)
- Answers are approximate if inactive DOFs move or generate significant power in real system

When more complete models are required

- Even if there are advantages to “targeted” model simplification, some questions require more complete models
  - Ex., Questions involving the double support phase of walking. Can’t prescribe trunk and lock ankle during push off.
- However, when higher DOF models are required, it remains to be demonstrated that induced acceleration results can be “pieced together” and combined with mechanical intuition to make useful clinical recommendations
  - Task would seem very challenging given the acknowledged limitation of an instantaneous analysis
    - Many more potential state changes to keep track of in higher DOF model

Back to basics: What are induced accelerations?

- Viewpoint 1: Induced accelerations are potential effects
  - Instantaneous accelerations induced by applying an isolated force on a linkage system in the absence of all other forces
    - Or, instantaneous change in acceleration induced by increasing or decreasing an isolated force on a linkage system
  - Insight gained from examining of these potential effects (though limited) can be useful in the context of existing knowledge

- Viewpoint 2: Induced accelerations can be regarded as contributions to a motion
  - However, such an interpretation often create unreasonable “power flows” through segments and huge “contributed” accelerations that mostly cancel out
  - Problem gets worse with higher DOF model

End