

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

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## *Table of Contents*

### I. Energy Balance

|   |   |
|---|---|
| A. Shoe-ground element power .....        | 2 |
| B. Energy balance vs. superposition ..... | 5 |

### II. Velocity Contribution

|  |   |
|--|---|
| A. Coriolis/Centripetal contribution .....       | 9 |
| B. Contribution from motion-dependent GRFs ..... | 9 |

### III. Temporal development of contributed GRF and implications

|  |    |
|--|----|
| A. Contributed GRFs using different integration step sizes .....             | 11 |
| B. Implications: Trunk support and forward progression by VAS and GMAX ..... | 13 |
| C. Implications: Joint angular acceleration induced by gravity .....         | 15 |
| D. Implications: Backward walking analysis .....                             | 16 |

## I: Energy Balance

### A. Shoe-ground element power

Energy balance between musculotendon and muscle-induced power is a necessary check, but induced shoe-ground element power, which has been neglected, must be included (i.e., musculotendon power = induced segment power + induced shoe-ground element power). Power loss and exchange to the shoe-ground elements are large during the first 15% of the gait cycle (Fig. 1). A check that requires musculotendon power to equal induced segment power rejects potentially valid solutions in which muscles contribute substantially to the GRF (and, therefore, the shoe-ground powers) during early stance. For instance, Clay Anderson's GRF decomposition using hard constraints with inertial terms produced differences between musculotendon and induced segment powers but checked exactly when shoe-ground powers were included.

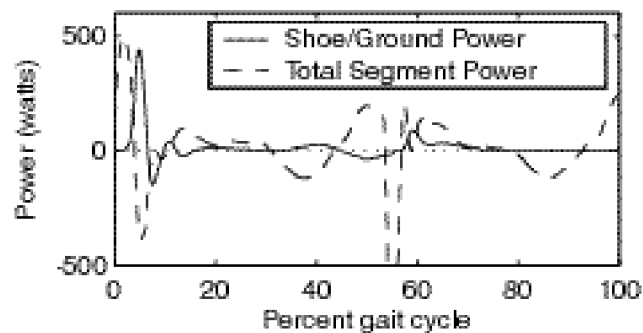


Fig. 1 Comparison of shoe/ground power with total segment power. Notice that shoe/ground power is substantial, especially during the first 15% of the gait cycle.

Using the integration method, differences between musculotendon and induced segment powers are larger using longer integration steps (examples for SOL and GMAX shown in Fig. 2A and 3A) but are primarily attributed to increases in induced shoe-ground powers (Fig. 4). When induced shoe-ground powers are included, differences between musculotendon and induced powers is negligible for step sizes from 0 to 11 ms (Fig. 2B and 3B,  $dt = 0.0, 2.2,$  and  $11.0$  ms). Power imbalances only become evident using an integration step of 22 ms, due to state changes during the long integration interval, but are often not great (Fig. 2B and 3B,  $dt = 22.0$  ms). Ironically, when induced shoe-ground power is neglected, musculotendon power only equals

induced segment power when none of the GRF is attributed to muscle (Fig. 2A and 3A,  $dt = 0.0$  ms).

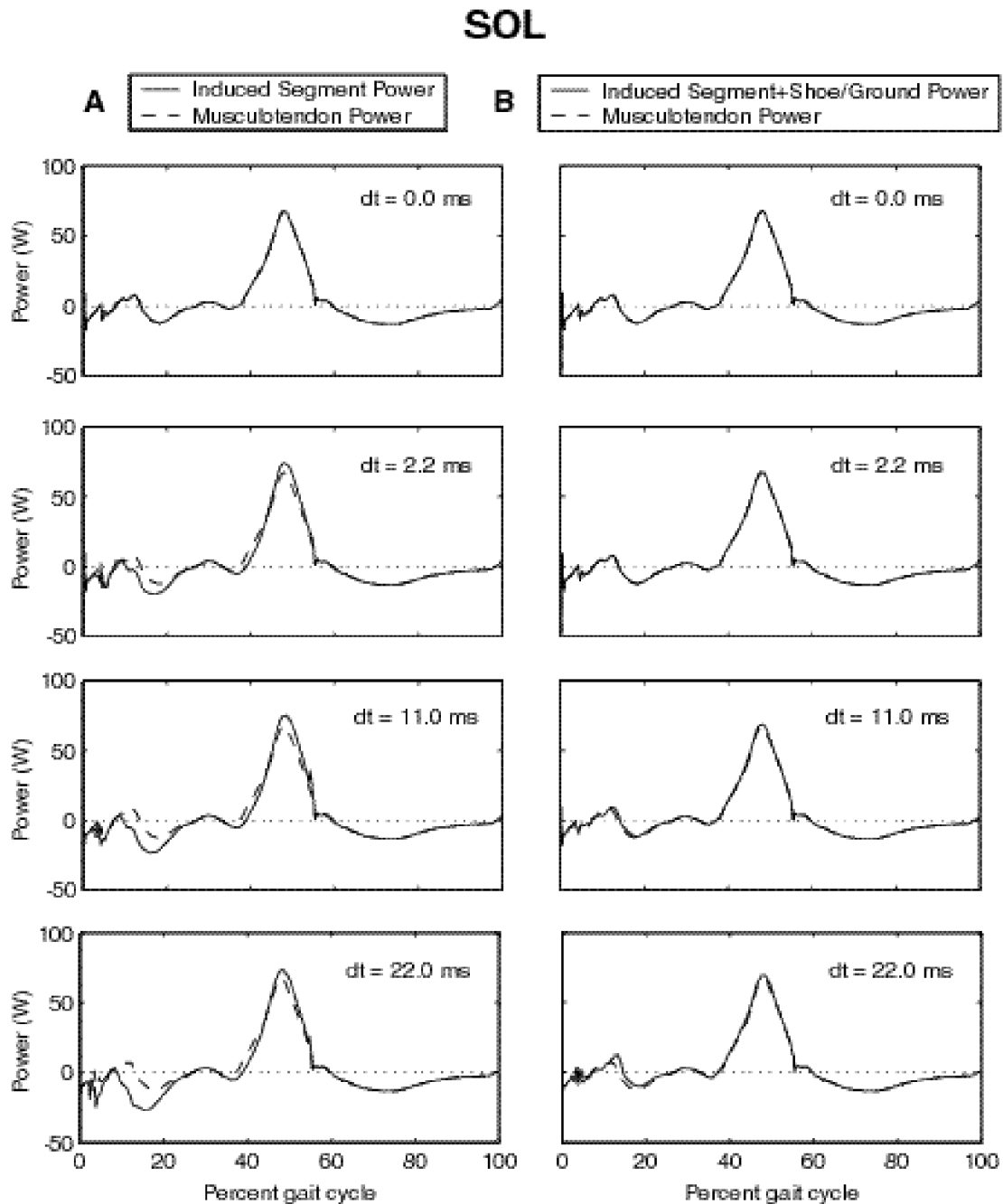


Fig. 2 Comparison of musculotendon power with induced segment and induced segment + shoe/ground power for SOL using different integration step sizes. Notice that differences between musculotendon and induced segment powers increase with integration step size, but when induced shoe/ground powers are included, differences are negligible for step sizes up to 11.0 ms.

## GMAX

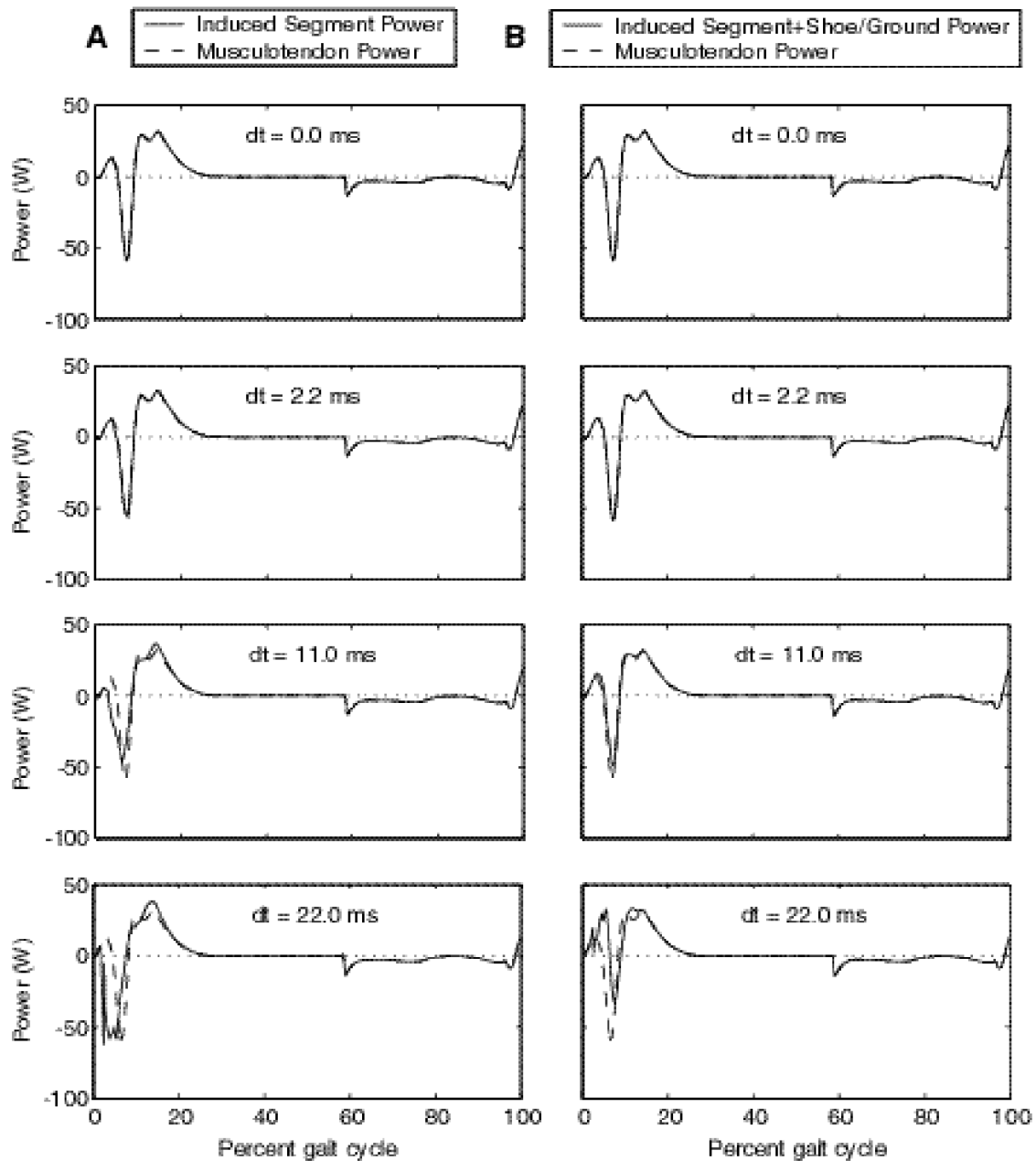


Fig. 3 Comparison of muscletendon power with induced segment and induced segment + shoe/ground power for GMAX using different integration step sizes. Notice that differences between muscletendon and induced segment powers increase with integration step size, but when induced shoe/ground powers are included, differences are negligible for step sizes up to 11.0 ms.

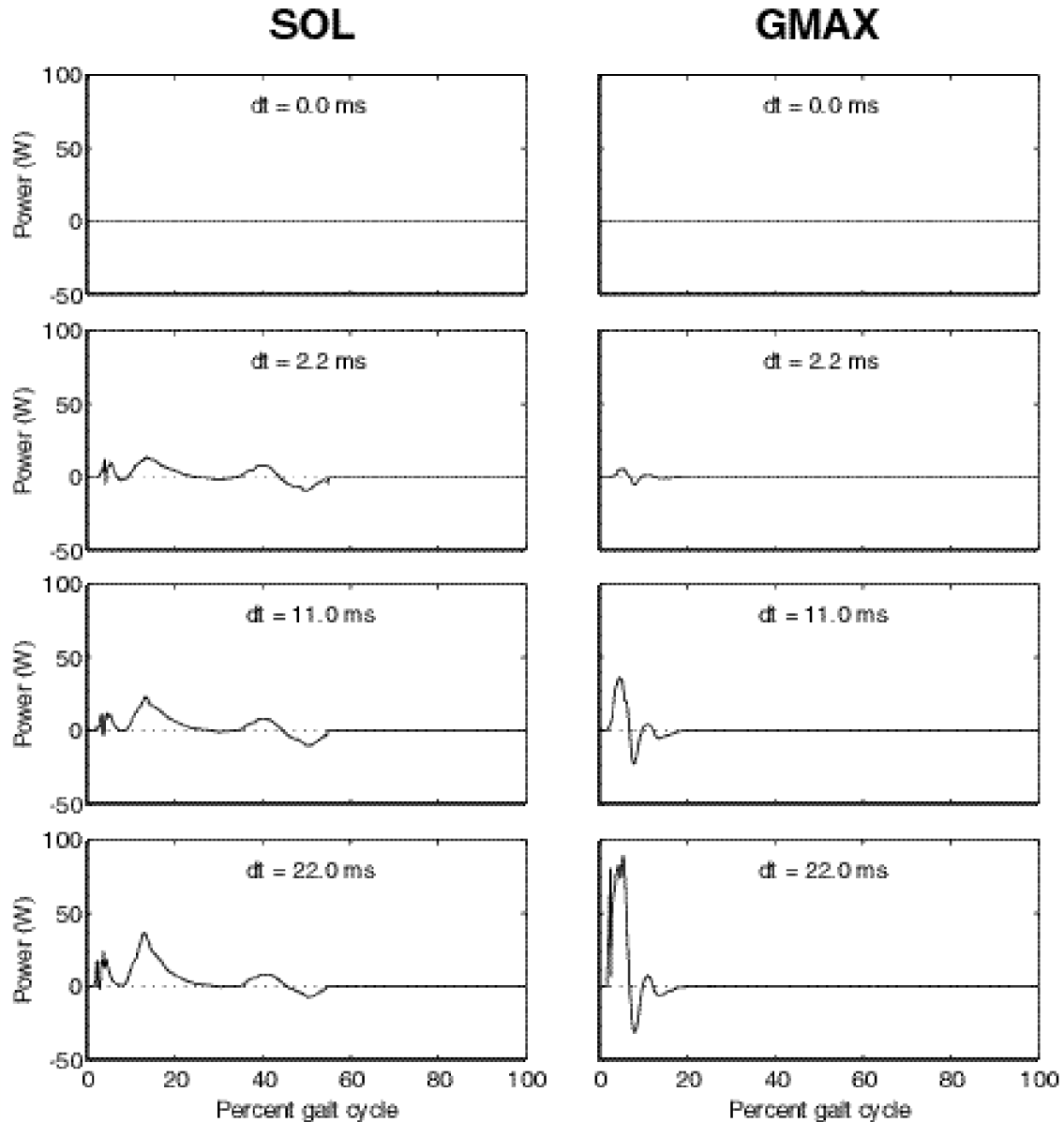


Fig. 4 Comparison of induced shoe-ground powers using different integration step sizes. Notice that induced shoe-ground powers increase with integration step size, especially for GMAX (a more proximal muscle) during early stance.

## B. Energy balance vs. superposition

Although a necessary check, an energy balance (i.e., musculotendon power = induced segment power + induced shoe-ground power) does not imply superposition (i.e., total induced accelerations / segment powers from muscles, passive forces, gravity, and velocity = simulated accelerations / segment powers). Even if the total induced power from each muscle matches its

musculotendon power, the power can be distributed to the wrong segments (ex., trunk vs. right leg) and/or wrong components (ex., vertical power vs. rotational) such that induced powers are inconsistent with the simulation. The logic that “if the powers add up, the accelerations must add up”, only makes sense if you’re referring to a superposition check on power and a superposition check on acceleration.

For example, using the current integration step of 2.2 ms, muscles from the right leg generate too much power to the trunk and absorb too much power from the right leg during early stance (Fig. 5A). As a result, the net induced trunk and leg powers from all muscles, passive forces, and gravity greatly differ from the simulated powers during early stance (Fig. 5B). However, the net induced powers from the right leg muscles are very close to their musculotendon powers because the excess power generated to the trunk balances the excess power absorbed from the right leg during early stance (Fig. 5A and B).

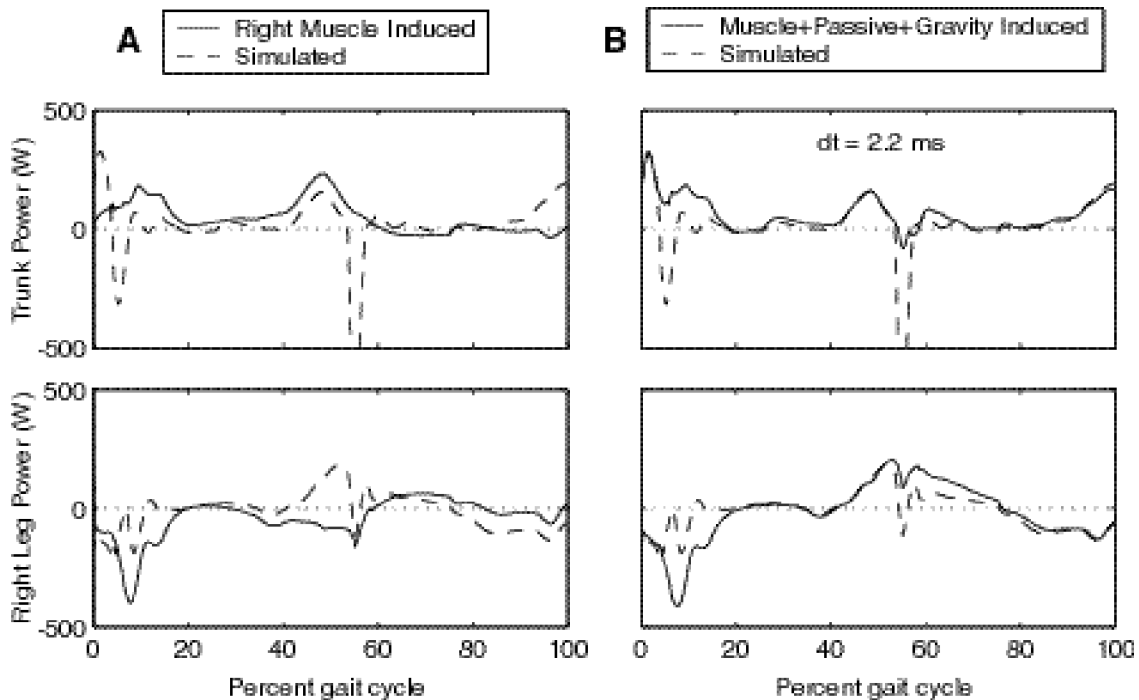


Fig. 5 Induced trunk and right leg powers from right leg muscles and all accounted for sources compared to the powers produced in the simulation ( $dt = 2.2$  ms). Notice the large differences between induced and simulated powers during the first 25% of right stance, because right leg muscles generate too much power to the trunk and absorb too much from the leg.

The large differences between induced and simulated powers during early stance are currently attributed to velocity; but velocity contributions are not calculated. However, vastly different distributions of induced trunk and leg powers are produced using different integration step sizes (Fig. 6). Velocity should not be arbitrarily assumed to account for any of these differences between induced and simulated powers, especially when there's not a conceptual reason why an energy balance should imply superposition. Moreover, differences between induced and simulated powers during early stance are not so inflated with larger integration step sizes (Fig. 6,  $dt = 11$  and  $22$  ms).

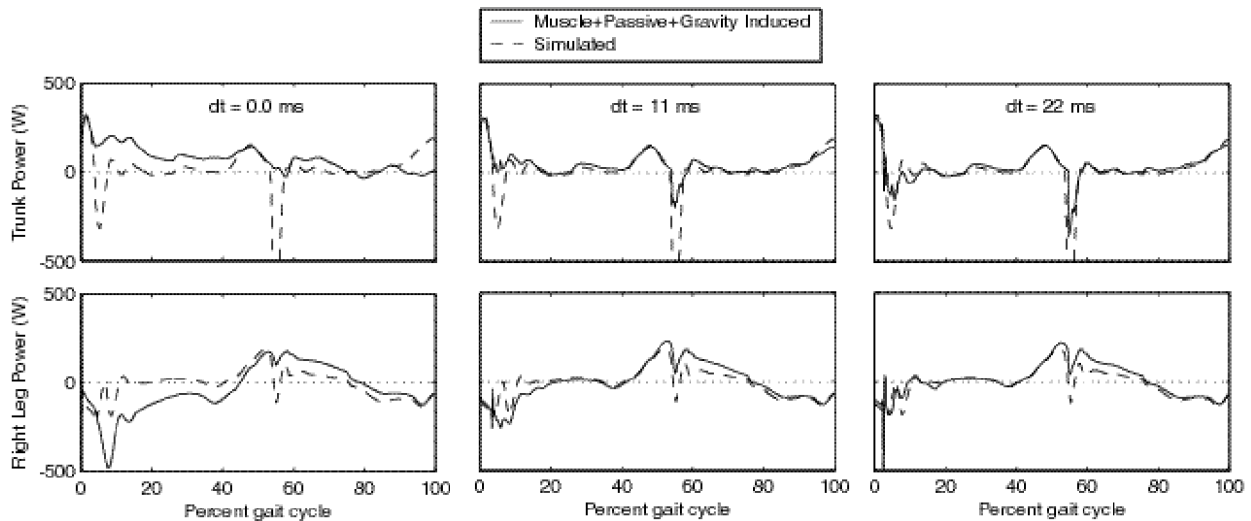


Fig. 6 Induced trunk and right leg powers using different integration step sizes. Step size = 2.2 ms is shown in Fig. 5B. Notice that too much power is generated to the trunk and too much absorbed from the right leg throughout stance when muscle contributed GRFs are neglected ( $dt = 0.0$  ms). Differences between induced and simulated powers are not so inflated using longer integration steps ( $dt = 11.0$  and  $22.0$  ms).

When induced leg power is further decomposed into induced thigh, shank, and foot powers, which are expected to be more sensitive to the GRF decomposition, they greatly differ from the corresponding simulated powers throughout the entire gait cycle (Fig. 7). Velocity contribution would need to be interpreted to be large throughout the gait cycle. The comparison only gets worse when segment powers are decomposed into horizontal, vertical, and rotational components. All of these results suggest that muscle-induced powers are distributed incorrectly, and that differences between induced and simulated powers are primarily attributed to error in the GRF decomposition, and not velocity.

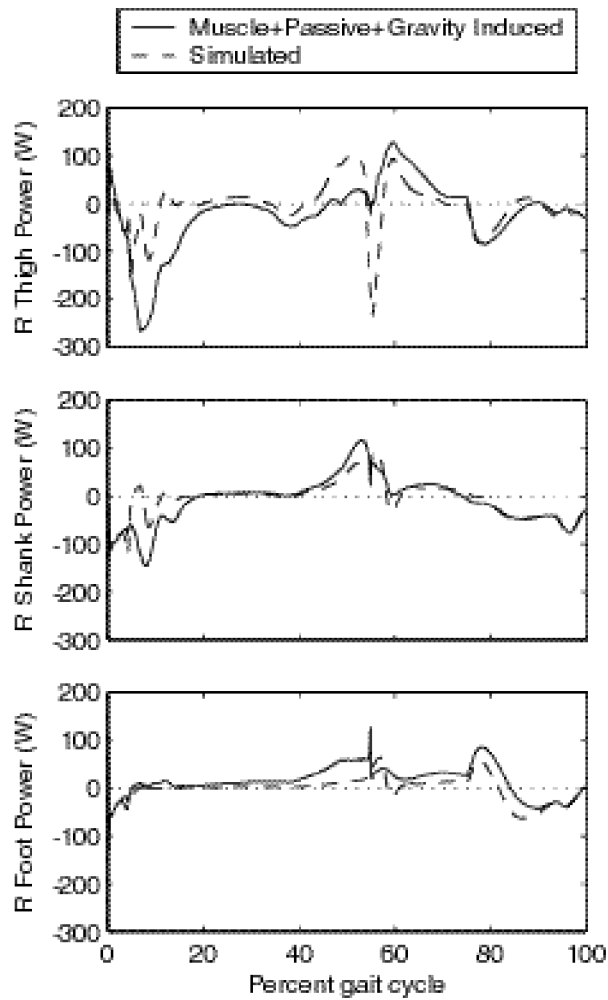


Fig. 7 Induced thigh, shank, and, and foot powers compared to simulated powers ( $dt = 2.2$  ms). Notice how induced powers to the leg segments differ from the simulated powers even during phases when induced powers to the right leg (segments combined) matches simulated powers (see Fig. 5B).

## II. Velocity Contribution

### A. Coriolis/Centripetal contribution

The segment powers induced by coriolis/centripetal forces (without motion-dependent GRFs) are relatively small compared to powers induced by muscles, passive forces, and gravity (compare Fig. 8 with 5B), and cannot account for the current differences between induced and simulated powers during early stance. In fact, coriolis/centripetal contributions are particularly small throughout stance and somewhat larger during swing when the segment angular velocities are greater. Note: Differences between contributions during stance and swing cannot be seen at scales that show the simulated powers, as in Fig. 8.

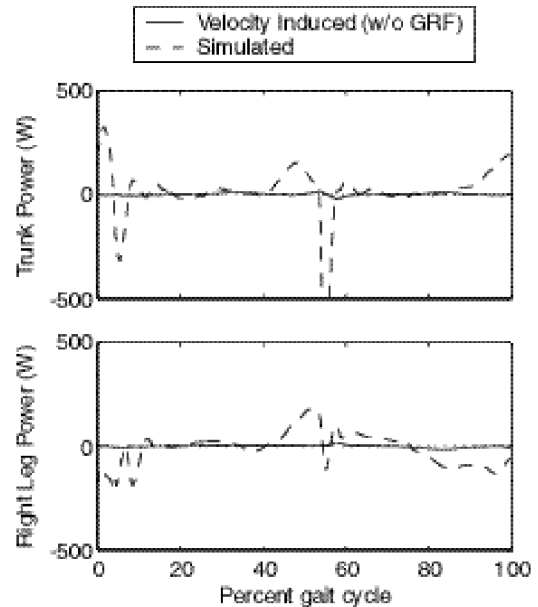


Fig. 8 Trunk and right leg powers induced by centripetal/coriolis forces (w/o GRF contribution).

### B. Contribution from motion-dependent ground reaction forces

The segment powers and accelerations induced by motion-dependent GRFs cannot be determined using the integration method but are inferred to be large, especially during the first 20% of the gait cycle when the simulated vertical GRF is mostly unaccounted for (Fig. 9) and attributed to velocity. However, muscle and gravity are expected to begin contributing to the vertical GRF as soon as the shoe-ground elements

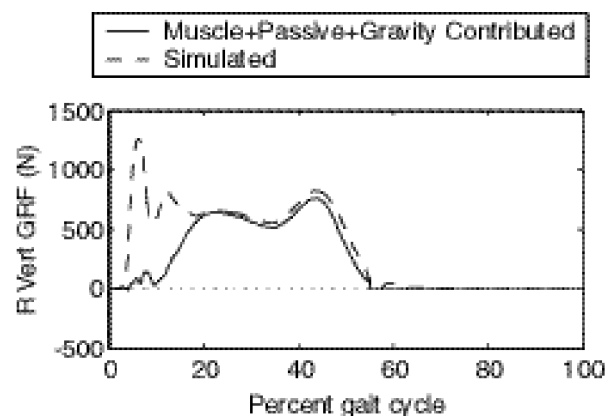


Fig. 9 Vertical GRF contributed by muscle, passive forces, and gravity (total accounted) compared to simulated vertical GRF ( $\Delta t = 2.2$  ms).

compress and not remain close to zero until about 12% of the gait cycle when the plantarflexors

begin to support body. Even though the damping component of the GRF attributed to the velocity of the foot moving into the ground may be high at heel impact, the component should lessen as the shoe-ground elements compress and the foot slows.

In order to approximate the motion-dependent GRFs, we set muscle, passive, and gravity forces to zero at the moment of heel impact and ran the simulation forward. The foot impacting the ground produced a spike in the vertical GRF, which was centered on the nominal impact spike, but it lasted no longer than 7% into the gait cycle (Fig. 10). Even during the first 7% of the gait cycle, the spike did not account for all of the vertical GRF (compare Fig. 9 to 10).

The results support the intuitive view that forces beside velocity contribute to the vertical GRF during early stance, and current differences in induced and simulated powers caused by motion-dependent GRFs are much inflated.

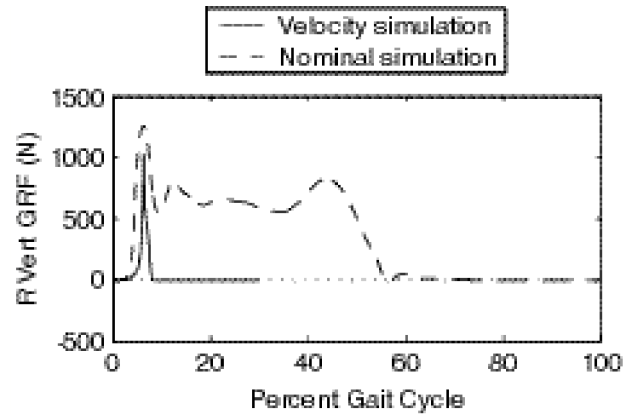


Fig. 10 Vertical GRF produced when muscle, passive, and gravity forces are set to zero at heel impact (velocity simulation).

### III. Temporal development of contributed GRF and implications

The current integration method essentially interprets a muscle's function to be its instantaneous action plus the action of its contribution to the history-dependent GRF during the previous 2.2 ms. In order for contributed GRFs to develop in the shoe-ground elements, changes in the position and velocity of the foot are necessary. If the shoe-ground elements are stiff and well-damped, and the muscle's action at the foot is fast (like for GAS and SOL, which act directly on the foot), the shoe/ground elements can equilibrate during a short 2.2 ms integration step and capture most of the muscle's contributed GRF. However, a 2.2 ms integration may not adequately capture the contributed GRF of muscles that act proximally at the hip and knee (i.e., VAS and GMAX) and of gravity, which acts on the whole body. The time responsive of the GRF to a force in the simulation depends not only on the intrinsic spring dynamics of the shoe-ground elements but also on the effective mass that interacts with the force and shoe-ground elements.

#### A. Contributed GRFs using different integration step sizes

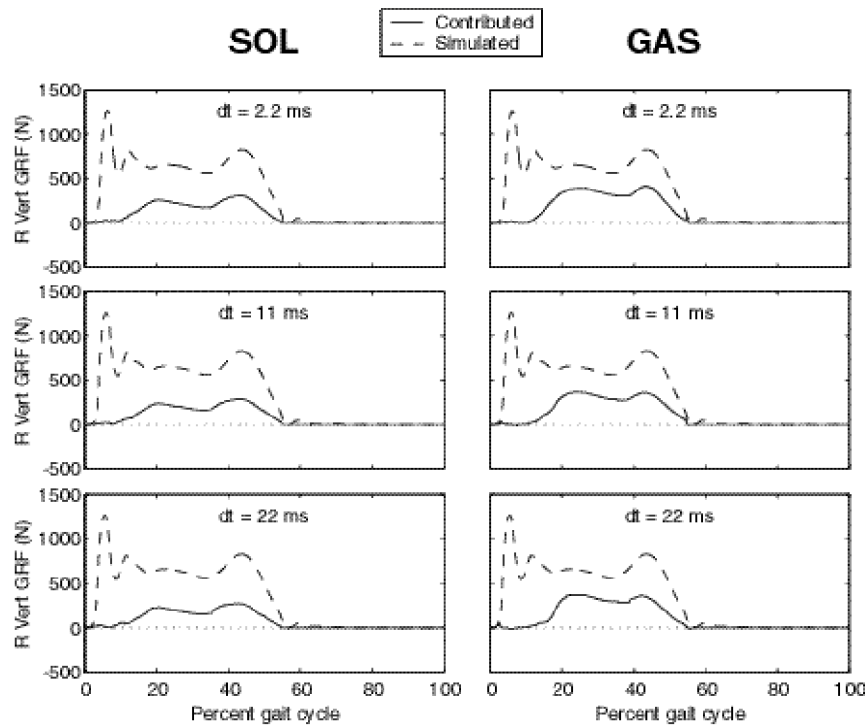


Fig. 11 The contributed vertical GRF from SOL and GAS using integration step sizes of 2.2, 11, and 22 ms.

If the shoe-ground elements have equilibrated after a designated integration step, the muscle's contributed GRF would not be expected to increase appreciably using longer integration steps. For example, the contributed vertical GRF from SOL and GAS remain about the same when integration step size is increased from 2.2 to 22 ms (Fig. 11).

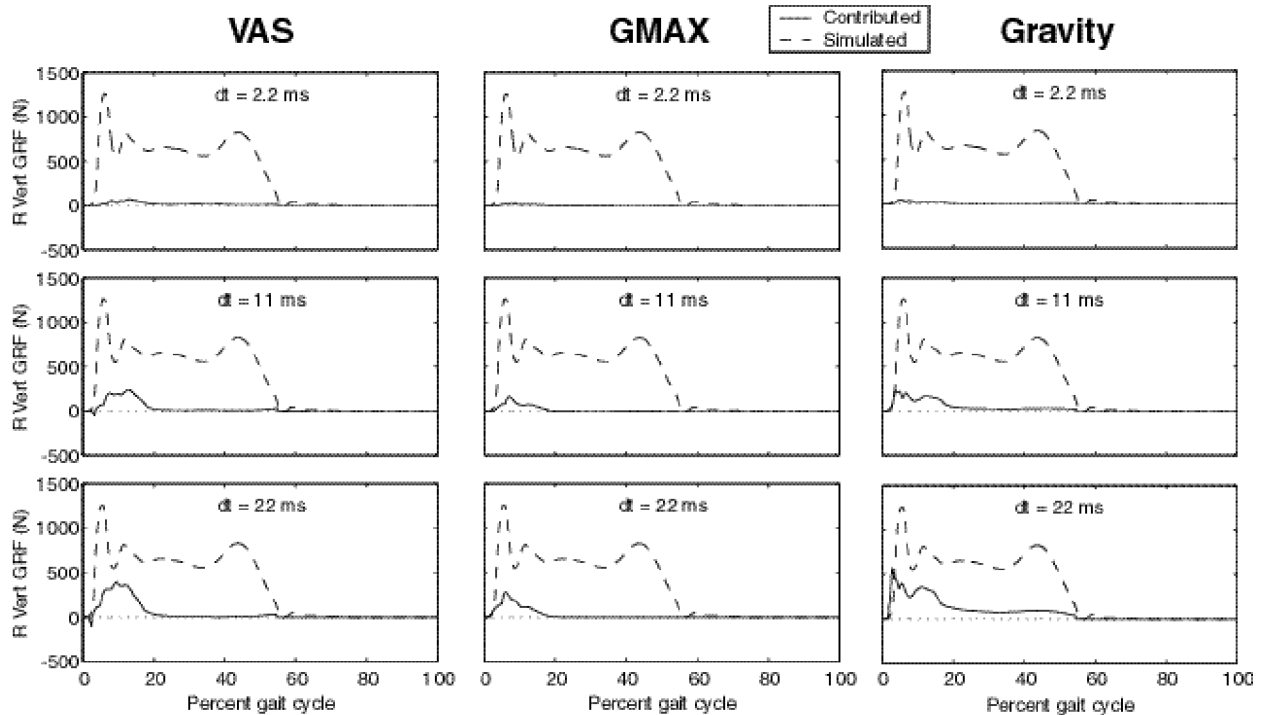


Fig. 12 The contributed vertical GRF from VAS, GMAX, and gravity using integration step sizes of 2.2, 11, and 22 ms.

However, the contributed vertical GRF from VAS, GMAX, and gravity increase monotonically when integration step size is increased from 2.2 to 22 ms (Fig. 12), suggesting that a 2.2 ms interval is not adequate and likely only captures a small fraction of the contributed vertical GRF from VAS, GMAX, and gravity.

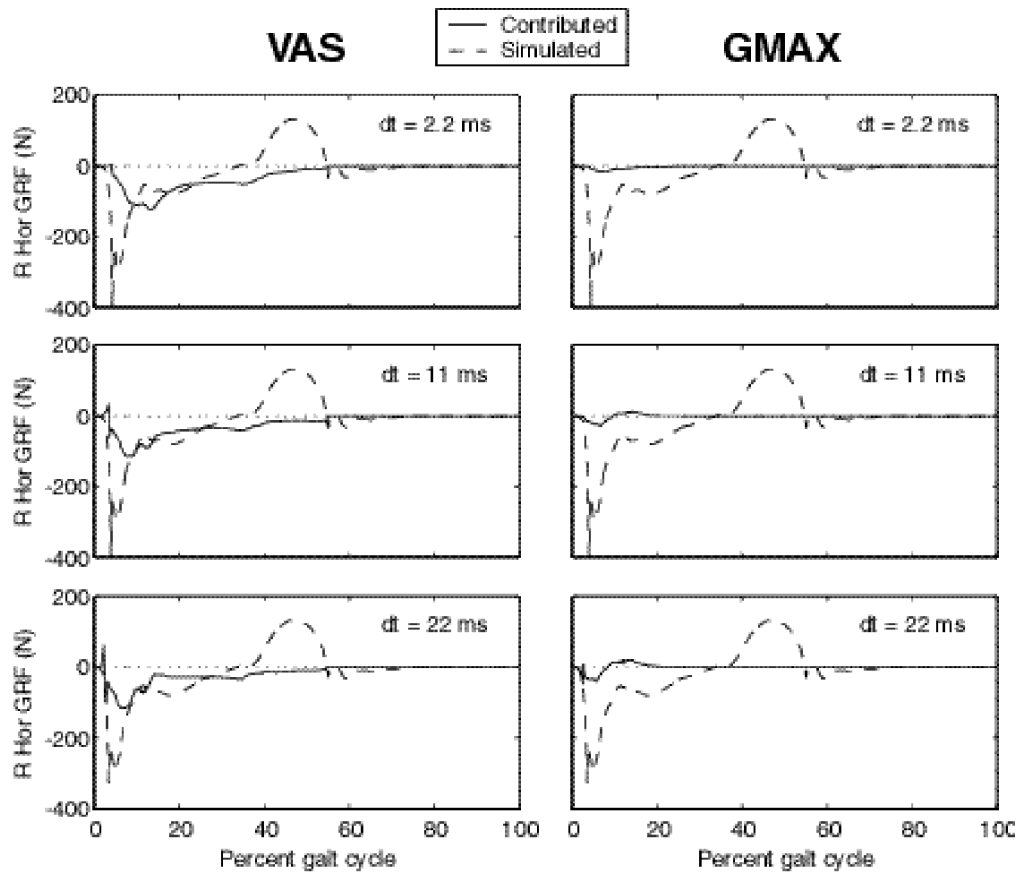


Fig. 13 The contributed horizontal GRF from VAS and GMAX using integration step sizes of 2.2, 11, and 22 ms.

Interestingly, the contributed horizontal GRF from VAS and GMAX do not increase as appreciably when integration step size is increased from 2.2 to 22 ms (Fig. 13), probably because the “coulomb” friction model of the horizontal GRF reacts more quickly than the vertical GRF. However, since the “coulomb” friction model lacks a velocity-independent term, its questionable whether the horizontal GRF can even equilibrate.

#### B. Implications: Trunk support and forward progression by VAS and GMAX

The role of VAS and GMAX in trunk support and forward progression are sensitive to integration step size. Using an integration step of 2.2 ms, trunk support from VAS and GMAX is limited and comes almost exclusively from accelerating the leg down into the ground, because the legs can't push off the ground when the contributed vertical GRF is so small. The resultant GRF from VAS and GMAX, directed more strongly backward than upward (not toward the hip),

primarily brake the leg and less the trunk. As a result, these muscles are found to accelerate the trunk (Fig. 14,  $dt = 2.2$  ms) and brake the leg during early stance. However, too much power is generated to the trunk and too much absorbed from the leg (Fig. 5B). To enforce superposition during early stance, velocity is interpreted to support the body (Fig. 9, unaccounted for GRF during first 20% of the gait cycle), decelerate the trunk (Fig. 5B, trunk power), and accelerate the leg (Fig. 5B, leg power).

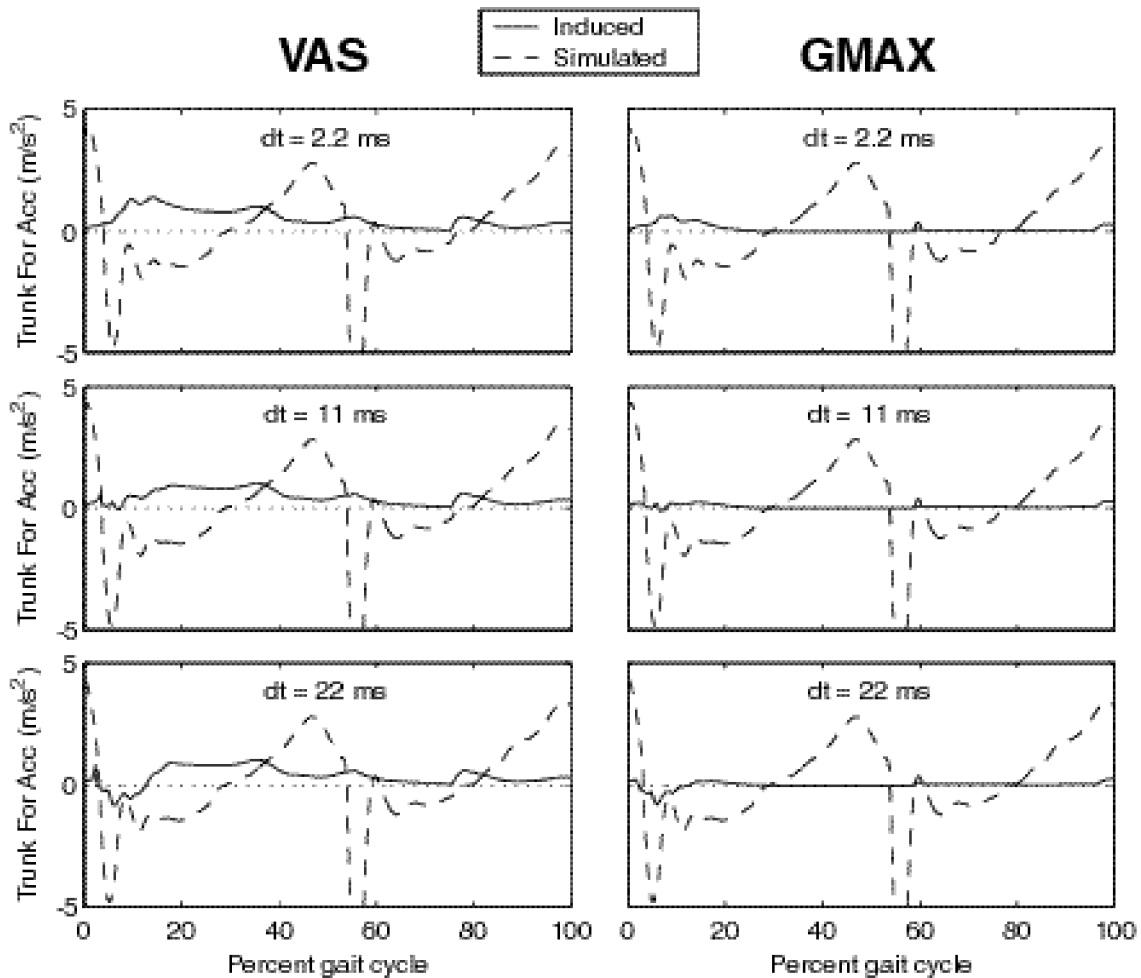


Fig. 14 Induced trunk forward acceleration (progression) by VAS and GMAX using integration step sizes of 2.2, 11, and 22 ms. Using longer integration step sizes, both VAS and GMAX decelerate the trunk in the direction of progression.

Using longer integration steps, the contributed vertical GRF from VAS and GMAX are larger, and the resultant GRF, directed more strongly upward than backward (toward the hip), brakes both the trunk and leg in the direction of progression. The net action on the trunk (instantaneous

muscle + contributed GRF) during early stance can be neutral or braking (Fig. 14,  $dt = 11$  and  $22$  ms). These results are more consistent with the view that muscles stiffen the leg, so that it acts like an inverted pendulum during early stance, exchanging kinetic energy for potential energy of gravity. Using longer integration steps, velocity contributions to body support (Fig. 15), trunk power, and leg power are also not so inflated during early stance (Fig. 6,  $dt = 11$  and  $22$  ms).

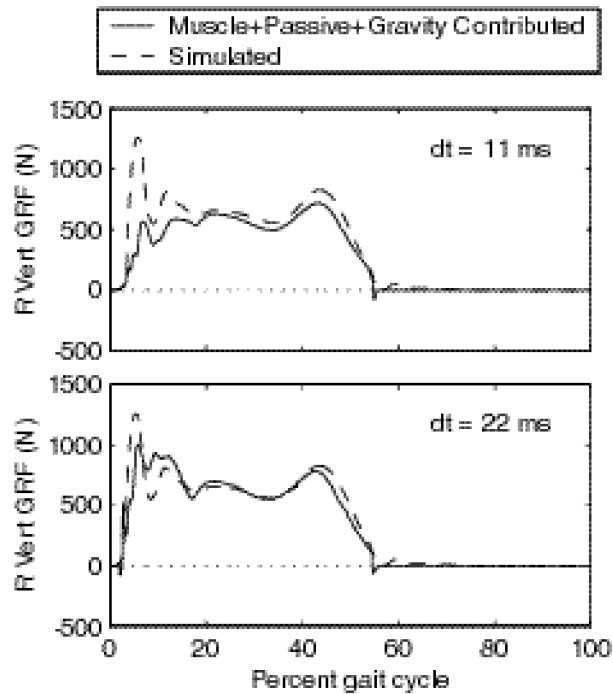


Fig. 15 Vertical GRF contributed by muscle, passive forces, and gravity (total accounted) compared to simulated vertical GRF using integration step sizes of 11 and 22 ms.

### C. Implications: Joint angular acceleration induced by gravity

Perhaps, the most glaring problem with the current acceleration results using an integration step size of 2.2 ms is the lack of sufficient joint flexion acceleration induced by gravity. Since gravity accelerates all the body segments equally downward, an appropriate level of GRF is needed to flex the joints such that the legs interact properly with the ground. Using an integration step of 2.2 ms, gravity accelerates the body downward essentially as a unit without significant joint flexion acceleration, while muscles support the trunk by accelerating the joints strongly into extension, which causes an imbalance of joint extension acceleration throughout stance (Fig. 16).

The GRF from gravity is undeniably underestimated unless velocity is interpreted to induce strong flexion acceleration throughout stance.

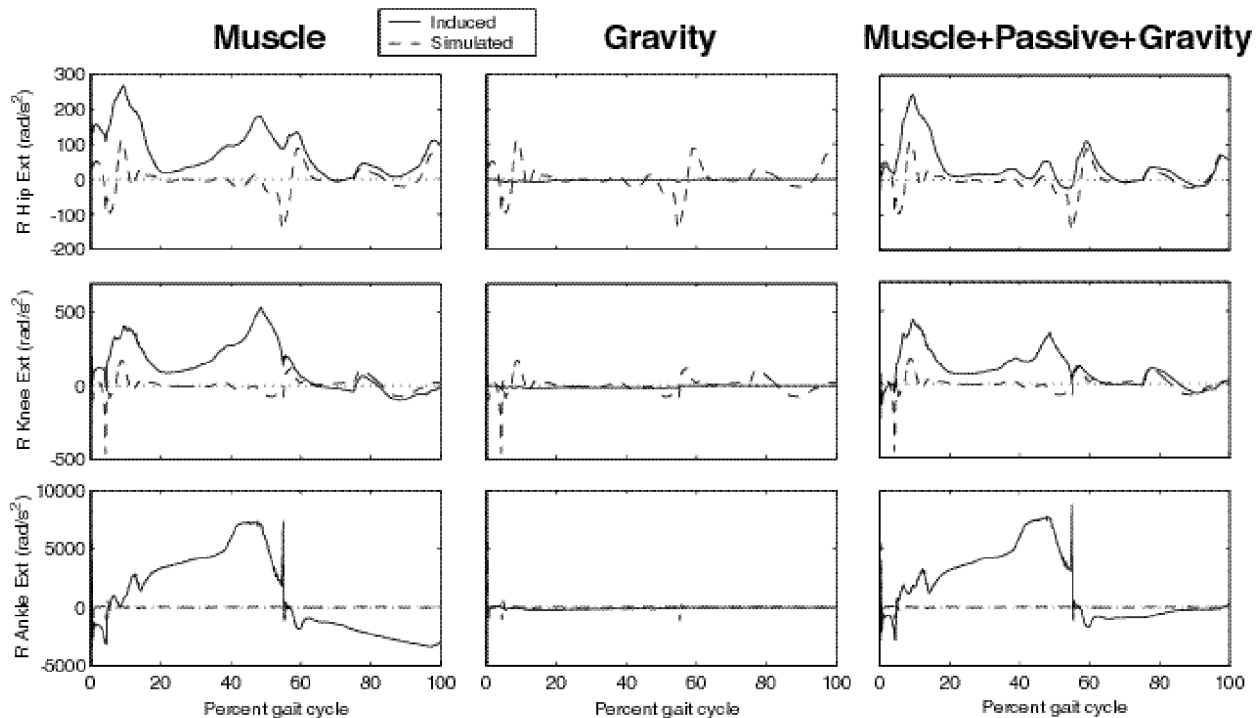


Fig. 16 Hip, knee, and ankle angular acceleration induced by muscle, gravity, and muscle+passive forces+gravity (total forces accounted) compared to the simulated accelerations. Notice that muscles extend the joints strongly throughout stance to support the trunk, while gravity does not flex the joints appreciably because its contributed vertical GRF is underestimated (i.e., the body just falls as a unit). Note: The simulated ankle accelerations cannot be seen clearly because they are transient and much smaller than induced accelerations through most of stance.

#### D. Implications: Backward walking analysis

The problems associated with the functional roles of VAS and GMAX to body support and trunk progression are expected to become more evident in an analysis on backward walking. From all indications, most of the vertical GRF unaccounted for during early stance is not attributable to velocity but to slow-acting muscle and gravity forces outside the 2.2 ms integration window. For this reason, most of the vertical GRF is expected to be unaccounted for whenever the fast-acting plantarflexors don't support the body -- whether its during early stance in forward walking or late stance (heel off) in backward walking. However, attributing almost all of the vertical GRF to velocity during late stance in backward walking, long after foot strike, is even more difficult to justify.

Moreover, since body configuration at heel off in backward walking is similar to that at heel strike in forward walking, VAS and GMAX are expected to accelerate the trunk anteriorly and leg posteriorly as in forward walking, except these actions brake the trunk and accelerate the leg in backward walking. In this case, too much power would be absorbed from the trunk and too much generated to the leg, and velocity would need to accelerate the trunk and brake the leg to enforce superposition during the propulsive phase of heel off. In fact, using an integration step of 2.2 ms, muscles are likely to brake the body through most of stance in backward walking, just as they contribute to forward progression through most of stance in forward walking. Both conclusions should appear suspect given the steady state nature of walking, but muscles braking the body, and velocity restoring the energy during backward walking is harder to accept.

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