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Induced acceleration contributions to locomotion dynamics are not physically well defined

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Abstract

Induced acceleration analysis quantifies the contributions of individual moments and forces to the accelerations, reaction forces, and powers produced during a task. The analysis has been advocated in the assessment of muscle and joint moment function during locomotion. However, results and interpretations drawn from the analysis have differed considerably between studies. The purpose of this paper is to assess whether induced acceleration contributions to locomotion dynamics are physically well defined. The assessment was facilitated by the analyses of a simple, theoretical locomotor task using different models. The task was based on a planar, rigid-body simulation in which joint moments at the hip, knee, and ankle posturally supported the configuration of the body as it rolled forward in a pendular motion. Induced acceleration analyses were performed using four models that completely described the simulated dynamics of the task but represented progressively fewer degrees of freedom. The contributions of each joint moment to the ground reaction force and trunk and leg powers differed between models, even though the net contributions were identical for all models and consistent with the simulation. Moreover, when all body degrees of freedom were represented in the model, large power redistributions between the trunk and leg were attributed to individual joint moments. However, these redistributions mostly cancelled such that the net redistribution was modest. In a single-segment model, this net redistribution was attributed entirely to gravity, without any cancellation of power flows. To conclude, induced acceleration contributions to the dynamics of a task are not physically well defined. The application of the analysis in the assessment of muscle and joint moment function during locomotion should be critically reevaluated.

Keywords: Induced acceleration analysis; Computer simulation; Modeling; Biomechanics; Coordination; Gait

1. Introduction

Induced segmental acceleration and power analysis has been advocated in the assessment of muscle and joint moment function during locomotion and other tasks [1–6]. The analysis quantifies the contributions of individual moments and forces to the accelerations, reaction forces, and powers produced during a task [1–3,7]. Because of dynamic coupling, these contributions are often non-intuitive. In recent work, the analysis has been used to assess the role of individual muscles and joint moments in providing body support and forward progression during walking, by quantifying their contributions to the vertical and forward acceleration of the trunk [3,8–10] or center of mass [11,12], and delivering mechanical power to the trunk and legs [8,11,13]. Other work has examined the contributions of individual forces to knee flexion during swing [14,15] and hip and knee extension during stance [16]. The analysis can be used to infer muscle coordination principles [1–3] and potentially assist the diagnosis and treatment of gait pathologies [14–16]. However, certain issues have surfaced regarding the results obtained from the analysis and their appropriate interpretation [4–6,17].

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Although induced acceleration analysis can provide an objective decomposition of locomotion dynamics, results have differed depending on the model and simulation used [3,5,6,8,11,12,18]. When results differ, the results obtained from more complete models have been regarded as more accurate and valid [5,6,11,15]. Consistent with this view, Riley and Keriggan [18] proposed that analyses should be conducted with a model that represents as many body degrees of freedom as possible. Furthermore, Zajac et al. [4] proposed that muscle action is unique once all dynamics and body degrees of freedom are accounted for and advocated the analyses of more complex models to identify this uniqueness. However, Chen [17] suggested that certain results obtained from complex models are expressed differently in simpler models. For this reason, he felt that a better understanding of results obtained from simple and complex models is needed.

Induced acceleration analysis also attributes large segmental power redistributions (also described as power "flows" or "transfers" [13]) to individual muscle forces or joint moments during walking [2,3,8,11,13]. Zajac et al. [2] suggested that these power redistributions represent important contributions to the execution of complex locomotor tasks, since the energetic state of individual segments change throughout the movement. However, Chen [17] observed that much of the power redistribution attributed to individual muscles do not result in net changes in individual segmental energy but cancel instantaneously. He conjectured that these power flow cancellations result indirectly from muscle forces providing postural support (i.e., maintenance of the configuration of the body). Consistent with this observation, Siegel et al. [13] found that power redistribution by individual joint moments at the hip, knee, and ankle during walking tended to cancel without causing comparable net changes in individual segmental energy. Alternatively, they proposed that joint moments with contradictory effects are recruited to provide precise control of mechanical energy flow within the body [13].

The purpose of this paper is to assess whether induced acceleration contributions to locomotion dynamics are physically well defined. This assessment was facilitated by the analyses of a simple, theoretical locomotor task using different models. The task was based on a computer simulation, which eliminated uncertainties in biomechanical measurements and model parameters. The dynamics of the task was completely described by models of varying complexity, which facilitated the comparison of results obtained from different models. It is contended that the issues regarding the sensitivity of results to the model and the magnitude of power redistribution by individual moments and forces can be more easily appreciated in the analyses of a simple task. Moreover, if induced acceleration contributions to the dynamics of a simple task are not well defined and depend on model formulation, the application of the analysis in the study of complex locomotor tasks should be critically reevaluated.

2. Methods

The theoretical task was based on a planar, rigid-body simulation created using dynamical equations-of-motion generated by SD/FAST (Symbolic Dynamics, Inc., Mountain View, CA) (see Fig. 1). The body consisted of four rigid segments: the trunk (including the mass of the head and arms), and thigh, shank, and foot of the supporting leg. The contralateral leg was not included. Body segment parameters were based on data collected by Dempster [19] and scaled to represent a person of a height of 1.77 m and mass of 75 kg. Joint moments at the hip, knee, and ankle were prescribed to posturally support the configuration of the body (hip, knee, and ankle angles equal to 5, 10, and 5 degrees of flexion, respectively) as it rolled forward, in a pendular motion, over a pin joint connecting the tip of the foot to the ground. The initial angular position and velocity of the body were set so that its center of mass advanced 0.585 m in 0.40 s (average forward velocity = 1.46 m/s).

Induced acceleration analyses were performed, using four models (see Fig. 2), to determine the contributions of joint moments and gravity and centrifugal forces to the vertical and forward acceleration of the body's center of mass, by quantifying their contributions to the ground reaction force, and the mechanical power of the trunk and leg (i.e., thigh, shank, and foot). Model 1 represented all body degrees of freedom, and Models 2–4 represented progressively fewer degrees of freedom by locking the ankle, knee, and hip joints (see Fig. 2). Since these degrees of freedom were posturally supported and did not accelerate during the task, all four models completely described its

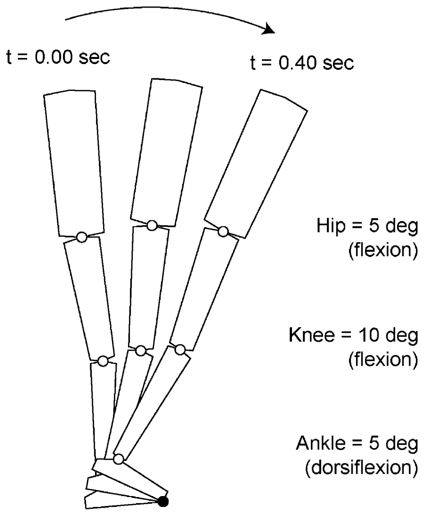

Fig. 1. Planar, rigid-body simulation representing the theoretical locomotor task. The body consisted of four rigid segments: the trunk, and the thigh, shank, and foot of the supporting leg. Moments at the hip, knee, and ankle posturally supported the joints at a constant 5, 10, and 5 degrees of flexion, respectively. The body rolled over a pin joint connecting the tip of the foot to the ground in a pendular motion, such that its center of mass advanced 0.585 m in 0.40 s.

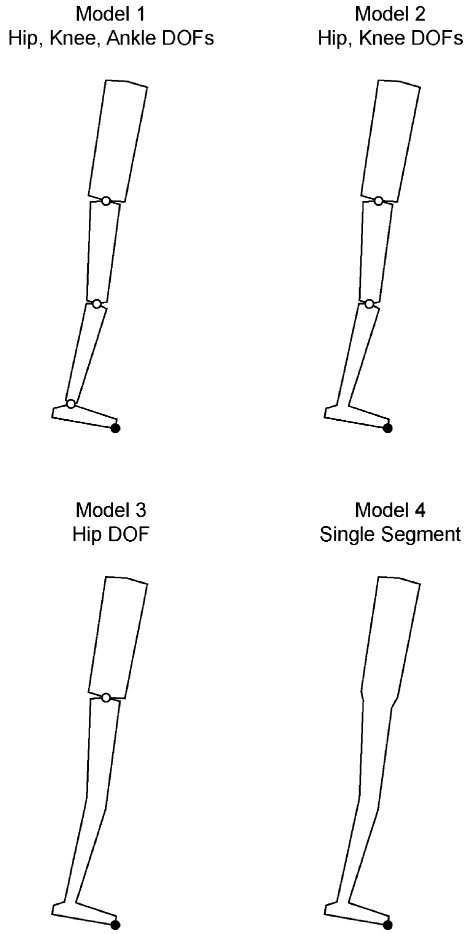

Fig. 2. Induced acceleration analyses were performed using four models that completely described the simulated dynamics of the task but represented progressively fewer degrees of freedom.

simulated dynamics. The method of computing induced accelerations and powers has been described in detail [2,8,12]. In summary, the contributions of each force (or moment) were determined using the state of the system at a given instant in time by setting all other forces to zero, applying the single force, and computing the resulting accelerations and reaction forces. Positive power delivered by a force to a segment indicated that the force accelerated the segment in the direction of movement; negative power indicated that the force decelerated the segment.

3. Results

An extensor moment at the hip, flexor moment at the knee, and plantarflexor moment at the ankle posturally supported the configuration of the body as it rolled forward (see Fig. 3). The body decelerated during the first half of the task, as kinetic energy was transformed to potential energy of gravity, and accelerated during the second half, as potential energy was transformed to kinetic energy. The total mechanical energetic state of the body was maintained throughout the task.

The vertical and horizontal ground reaction force (GRF) contributed by each moment or force differed (both in magnitude and direction) between models, even though the total contributions were identical for all models and equal to the simulated ground reaction force (see Fig. 4). In Model 1, the ankle moment was the primary contributor to the vertical ground reaction force, with other moments and forces contributing minimally. As the joints were progressively locked from the ankle to the hip in Models 2–4, more of the vertical ground reaction force was attributed to gravity and centrifugal forces and the moments acting at the proximal joints that were left unconstrained. In Model 4, the vertical and horizontal ground reaction forces were attributed entirely to gravity and centrifugal forces.

The mechanical power of the trunk and leg contributed by each moment or force also differed (both in magnitude and direction) between models (see Fig. 5). Since the joint moments did not generate nor absorb energy, they redistributed power between the trunk and leg such that the contributed leg powers were equal in magnitude to the contributed trunk powers but opposite in sign. In Model 1, the knee moment redistributed much power from the trunk to the leg (i.e., power contribution to leg was positive, contribution to trunk negative), but its effect was mostly cancelled from the power redistributed from the leg to the trunk by the hip and ankle moments (i.e., power contribution to trunk was positive, contribution to leg negative). As the joints were progressively locked in Models 2 and 3, the moments acting at the joints that were left unconstrained redistributed less power. In Model 4, the total redistribution of power from the trunk to the leg was attributed to gravity, without cancellation of power flows.

4. Discussion

Analyses of the theoretical locomotor task demonstrate that induced acceleration contributions to the dynamics of a task are not physically well defined. Even though all four models completely described the simulated dynamics of the task, the induced acceleration decomposition of reaction forces and powers differed between models. These differences cannot be attributed to estimation errors. Moreover, when all body degrees of freedom were represented in the model, large power redistributions were attributed to individual joint moments, but these redistributions mostly cancelled. As modeled degrees of freedom were reduced, less power redistribution was attributed to the moments that acted at the joints left unconstrained. In a single-segment model, the net redistribution was attributed entirely to gravity, without any cancellation of power flows.

Induced acceleration contributions are sensitive to the model representation of degrees of freedom that are posturally supported and do not accelerate during a task.

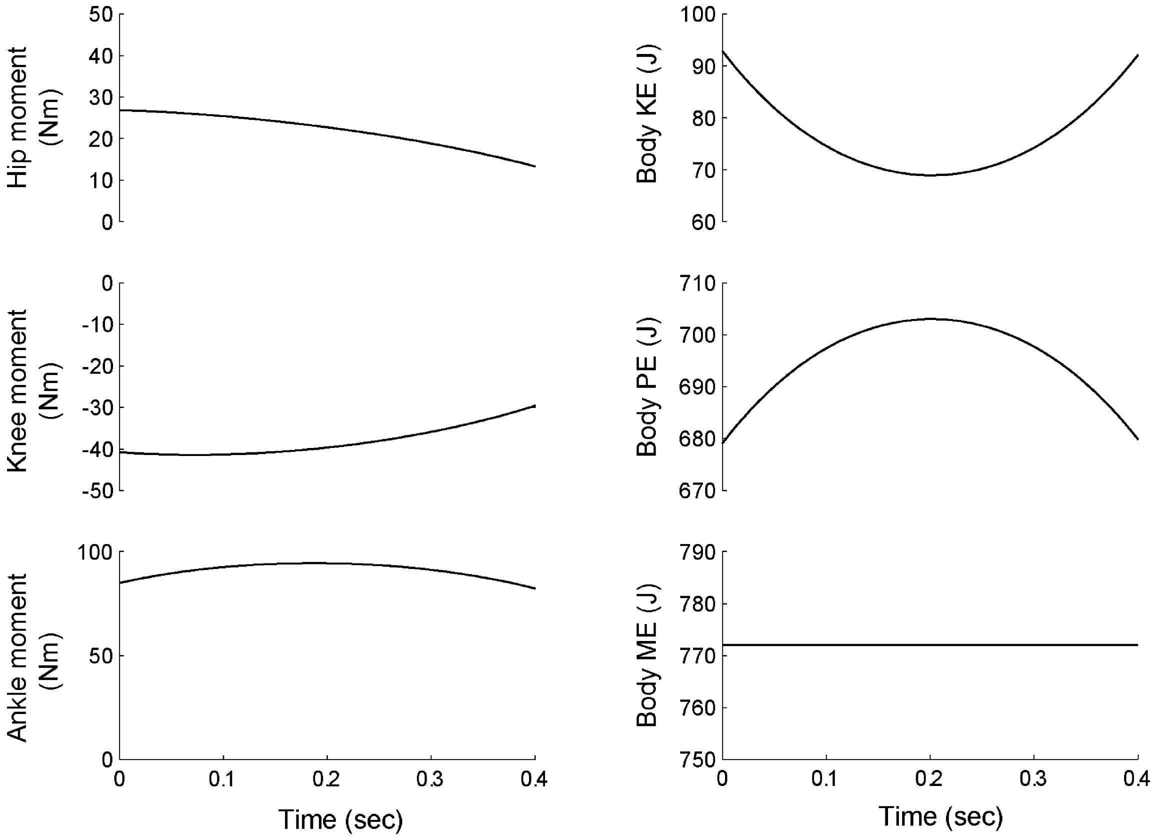

Fig. 3. Simulated joint moment and body energetic data for the theoretical task. Extensor and plantarflexion moments are represented as positive. The total mechanical energetic state of the body (ME) was maintained as changes in kinetic energy (KE) was reflected by changes in potential energy of gravity (PE).

Contributions depend on model formulation, because they are based on the potential, instantaneous effect of applying individual forces and not on observed or simulated dynamics. Even degrees of freedom that are posturally supported during a task can accelerate greatly when the effects of individual forces are determined in isolation. Thus, the addition or elimination of any degree of freedom in a model will significantly affect results from the analysis. For instance, if a toe degree of freedom was included in the analysis of the theoretical task, the toe moment would have been found to be the primary contributor to the vertical ground reaction force with the ankle moment contributing minimally (see Fig. 6). In contrast, biomechanical quantities that are physically well defined can be determined consistently using models of varying complexity and are insensitive to the representation of degrees of freedom that do not accelerate. For example, in the theoretical task, the calculated knee moment is the same, regardless of whether the posturally supported ankle is modeled as a constraint or degree of freedom.

The analyses of the theoretical task also demonstrate that the model representation of degrees of freedom that are posturally supported can result in greater power redistribution attributed to individual joint moments. These large power redistributions can be misleading, since they mostly cancel and do not contribute importantly to net changes in individual segmental energy. Moreover, the interpretation that these cancellations reflect a precise control of power flow by forces with contradictory effects, as suggested in analyses of walking [13], should be viewed critically. In the theoretical task, the joint moments simply maintained the configuration of the body as it rolled forward in a pendular motion. The moments did not absorb energy nor did they have opposing effects in a manner similar to muscle co-contraction at a joint. More appropriate is the interpretation that power redistribution by individual joint moments synergistically maintained the energetic state of segments. However, the contribution made by each joint moment is not well defined and multiple decompositions explain the net effect (see Fig. 5, decomposition of trunk and leg powers using Models 1–4). Indeed, the contributions could be regarded as artificial constructs of the decomposition technique, since they do not describe power flows that physically occur.

The important remaining question is whether induced acceleration contributions for any particular model represent meaningful descriptions of task function. The analyses of the theoretical task strongly suggest that these contributions do

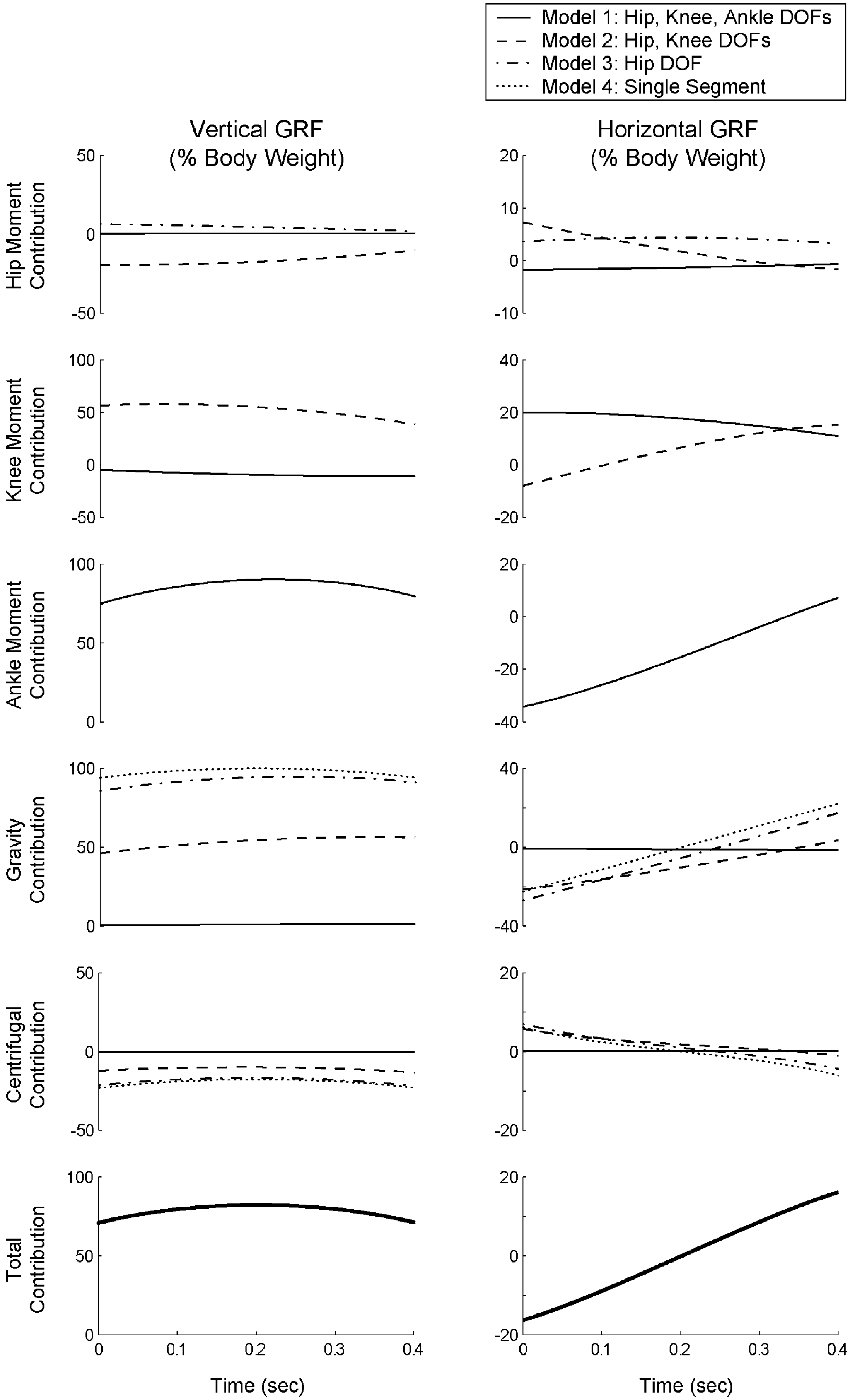

Fig. 4. Induced acceleration decomposition of the vertical and horizontal ground reaction force (GRF) using Models 1–4: contributed GRF from the hip, knee, and ankle moments and gravity and centrifugal forces and the total contribution from all moments and forces. The GRF contributed by each moment or force differed (both in magnitude and direction) between models, even though the total contributions were identical for all models.

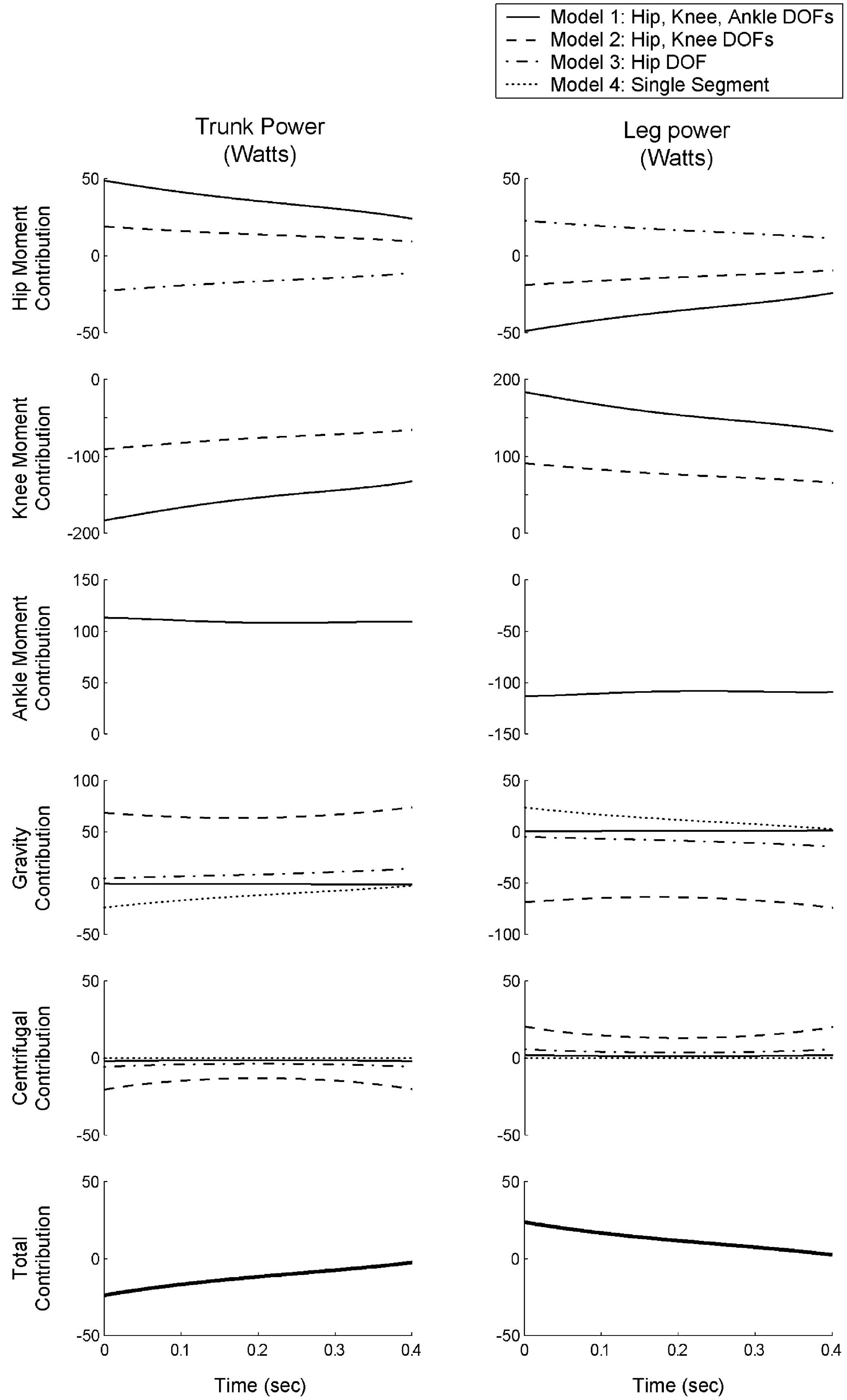

Fig. 5. Induced acceleration decomposition of the trunk and leg powers using Models 1–4: contributed power from the hip, knee, and ankle moments and gravity and centrifugal forces and the total contribution from all moments and forces. The power contributed by each moment or force differed (both in magnitude and direction) between models, even though the total contributions were identical for all models.

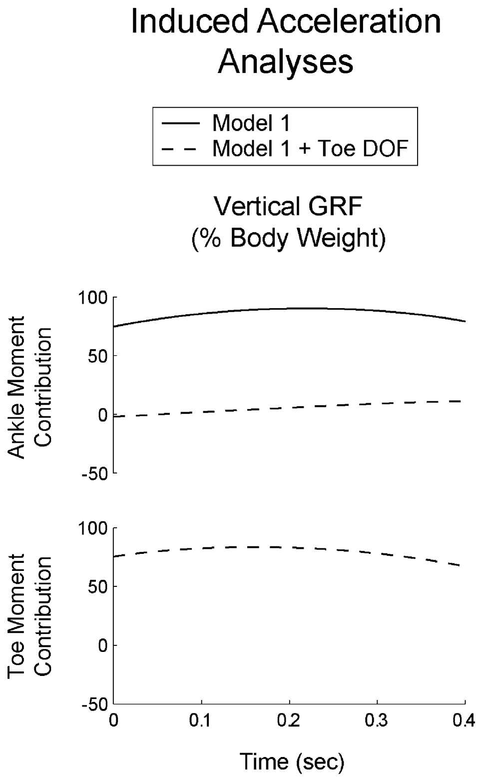

Fig. 6. If a toe degree of freedom was represented in the foot segment in Model 1, the toe moment would have been found to be the primary contributor to the vertical ground reaction force (GRF) with the ankle moment contributing minimally.

not represent meaningful descriptions. For instance, the contributions of individual muscles and joint moments to the vertical and forward acceleration of the trunk or center of mass have been used to assess their role in providing body support and forward progression during walking [3,8–12]. However, in the theoretical task, the vertical ground reaction force attributed to each joint moment, which accelerates the center of mass upwards, did not reflect the moment's importance to body support but, qualitatively, described its role in transferring weight to the ground. This is consistent with the strongest contributions shifting from gravity to the toe moment when degrees of freedom are added distally to the supporting leg (see Fig. 4, decomposition of vertical GRF using Models 1–4, and Fig. 6). Now, the addition of degrees of freedom distally (e.g., a toe degree of freedom) does not diminish the importance of the proximal joint moments in supporting the posture of the body, which prevents the body from collapsing. Furthermore, the positive horizontal ground reaction force attributed to each joint moment, which accelerates the center of mass forward, did not reflect the moment's importance in promoting body progression. In the complete model, the knee moment was found to accelerate the body forward throughout the task, while the hip and ankle moments, by and large, decelerated the body's forward motion (see Fig. 4, decomposition of horizontal GRF using Model 1). However, the interpretation that the knee moment promoted forward progression while the hip and ankle moments impeded progression belie the fact that the hip, knee, and ankle moments maintained the configuration of the body as it rolled forward.

In conclusion, the application of induced acceleration analysis in the assessment of muscle and joint moment function during locomotion should be critically reevaluated. Induced acceleration contributions to the dynamics of a task are not physically well defined, and analysis results depend on the model representation of degrees of freedom that are posturally supported and do not accelerate. Moreover, the model representation of degrees of freedom that are posturally supported can result in greater power redistribution attributed to individual joint moments. These large power redistributions can be misleading, since they mostly cancel and do not contribute importantly to net changes in individual segmental energy. The issues regarding the sensitivity of results to the model and the magnitude of power redistribution by individual moments and forces have surfaced in previous analyses of human locomotion [4–6,13,17,18]. However, inadequacy in the understanding of human locomotion dynamics and uncertainties regarding the accuracy and appropriateness of the analyzed models made the appreciation of these issues difficult. The analyses of the simple, theoretical task in this paper demonstrate that induced acceleration contributions are not physically well defined and may not represent meaningful descriptions of task function.

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