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Abstract: The goals of this study were to determine if the muscle contributions to vertical and fore-aft acceleration of the mass center differ between crouch gait and unimpaired gait and if these muscle contributions change with crouch severity. Examining muscle contributions to mass center acceleration provides insight into the roles of individual muscles during gait and can provide guidance for treatment planning. We calculated vertical and fore-aft accelerations using musculoskeletal simulations of typically-developing children and children with cerebral palsy and crouch gait. Analysis of these simulations revealed that during unimpaired gait the quadriceps produce large upward and backward accelerations during early stance, whereas the ankle plantarflexors produce large upward and forward accelerations later in stance. In contrast, during crouch gait, the quadriceps and ankle plantarflexors produce large, opposing fore-aft accelerations throughout stance. The quadriceps force required to accelerate the mass center upward was significantly larger in crouch gait than in unimpaired gait and increased with crouch severity. The gluteus medius accelerated the mass center upward during midstance in unimpaired gait; however, during crouch gait the upward acceleration produced by the gluteus medius was significantly reduced. During unimpaired gait the quadriceps and ankle plantarflexors accelerate the mass center at different times, efficiently modulating fore-aft accelerations. However, during crouch gait, the quadriceps and ankle plantarflexors produce fore-aft accelerations at the same time and the opposing fore-aft accelerations generated by these muscles contribute to the inefficiency of crouch gait.

1. Cover Letter (Author Agreement)

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Dr. Tim Theologis
Editor-in-Chief
Gait & Posture

Dear Dr. Theologis:

We thank the reviewers and editor for accepting our manuscript for publication in *Gait & Posture* as an Original Article. We have revised the manuscript based upon the suggestions and comments of the reviewers.

Each of the authors was fully involved in conducting the study and preparing the manuscript and concurs with the content of the final submission. The material within has not be submitted for publication elsewhere, except as an abstract and as part of a doctoral dissertation.

Please contact me if you have any questions.

Best regards,

Katherine M. Steele, PhD
Ajay Seth, PhD
Jennifer L. Hicks, PhD
Michael H. Schwartz, PhD
Scott L. Delp, PhD

Conflict of Interest Statement

None of the authors had financial or personal conflict of interest with regard to this study.

GAIPOS-D-12-00465 Revision

We thank the editor and reviewers for their critique and valuable additions to our manuscript. The sections below address each reviewer's suggestions with the reviewer's original text in italics followed by our response:

Reviewer #1:

With respect to the method section:
1. *' constraints on muscle excitations were used when the simulated muscle activity was inconsistent with the EMG signals' I would like to have some evidence where in the gait cycle these were imposed and how - could this be added to the supplementary material so that their effect on the underlying excitations can be evaluated.*

We have added a description of the constraints and bars to Supp. Fig. 1 to indicate when and how the constraints were applied.

2. *The authors present two analysis methods; there is no motivation as to why these two distinct parameters are used. This should be made explicit in the manuscript.*

We included the two analyses methods in order to evaluate (1) the relative timing and (2) the magnitude of the muscle contributions to fore-aft accelerations. We have clarified the purpose of each method in the manuscript (p. 6 ln. 18-24).

With respect to the results section:
1. *The authors state 'In the erect posture of unimpaired gait, a larger portion of body weight is supported by skeletal alignment than in a crouched posture and, thus, the acceleration of the mass center due to gravity is reduced'. For this they refer to figure 3 - however, it is left to the interpretation skills of the reader where they should find the information on skeletal alignment; Please clarify.*

We have moved the reference to Fig. 3B to the previous sentence which discusses the contribution of gravity to downward acceleration. We have also clarified the relationship between gravity and skeletal alignment in the caption of Fig. 3 and in the results (p. 7 ln. 8-12). We chose not to include the accelerations from gravity and skeletal alignment in Fig. 3B because this would provide redundant information.

With respect to the discussion section:
1. *The authors state ' These sustained contributions contribute to the inefficiency of crouch gait and require individuals with crouch gait to adopt a different strategy for speed modulation'. The gait pattern here is studied under steady state conditions; therefore it cannot be extrapolated to gait modulation. Probably it is just a terminology issue be more specific.*

We agree with the reviewer's comment. In the revised manuscript we refer to a previous simulation study which found that modulation of vasti and ankle plantarflexor activity during unimpaired gait provides an effective mechanism for modulating speed. Activity of the vasti and ankle plantarflexors can be proportionally increased or decreased during unimpaired gait to modulate speed. In the revised manuscript we first refer to this publication and then suggest that the sustained and opposing fore-aft accelerations during crouch gait limits the effectiveness of this mechanism to modulate speed. We have clarified this point in the discussion (p. 9 ln. 1-6).

2. *The relevance of the whole section in the discussion on the cost-function could be made more understandable for the clinician when you include the statement that therefore' the level of co-contraction between muscles will be minimized and that this may not be the best assumption in CP.'*

We agree with the reviewer that a different cost-function may be better for individuals with cerebral palsy and that we should clarify this point in the discussion. We have revised the discussion of the cost-function (p. 10 ln. 19-22). Our current cost-function (minimize the sum of squared activations) does not minimize co-contraction between muscles; however, we recognize that there may be other cost-functions that are more appropriate to pathologic gait.

3. *You need to acknowledge the limited number of patients in each of the categories, especially given the large variability in the msl excitations.*

As suggested, we acknowledge this limitation in the discussion (p. 10 ln. 22-24).

Reviewer #2:

1. *Could the authors add in table 1 the number of patients on each group and the number of patients for whom EMG data was available?*

We added the number of subjects and the number of subjects with EMG in each group to Table 1.

2. *In table 1 the standard deviation for the mass in the moderate crouch group is +-31Kg, this seems to be large considering the age and height do not differ as much. Could the authors verify this value?*

This value is correct. One of the moderate crouch gait subjects was obese, hence the large standard deviation.

3. *The authors averaged the experimental EMG data available for each group in order to compare qualitatively the muscle activations from the CMC. This assumes that the muscle activations are similar for all the patients within each group. My main concern is that different patients may exhibit different activation times even when the gait patterns are similar, particularly if there is co-contraction. Did the authors look at the variability of the experimental EMG data for each group to justify the use of the average EMG signals in patients for whom this data were not available?*

We agree with the reviewer that EMG patterns can vary between individuals with cerebral palsy, even among individuals with similar gait patterns. The supplementary figure shows the standard deviation in EMG data during unimpaired gait and mild and severe crouch gait which do exhibit variability between subjects. For the moderate crouch gait subjects we were not able to evaluate variability between subjects because EMG data was only available for one subject. Due to the variability between subjects we only applied on/off constraints during times that were consistent across subjects and did not constrain the shape of muscle activations to EMG data. We have expanded our discussion of constraints in the caption of Supp. Fig. 1 and expanded our discussion of the limitations of the EMG data in the manuscript (p. 10 ln. 15-19).

4. *In page 5 lines 17-19 the authors mention the use of constraints on muscle excitations when the simulated data was inconsistent with the EMG signals, could the authors indicate for how many subjects was this step necessary?*

This is a good suggestion. We have included bars on Supp. Fig. 1 to indicate the timing of constraints for each subject.

5. *The first paragraph on page 6 is describing results and some discussion and should be rearranged*

This paragraph describes how we evaluated the accuracy of the model prior to using it to answer the questions posed in this study. A detailed evaluation of the model is an essential part of the methods and was our rationale for including it in the methods, similar to previous simulation studies. Based on the reviewer's comment, to help the reader understand our rationale for including this paragraph in the methods, we have revised the paragraph's introduction to emphasize the need to evaluate the model before addressing the research questions (p. 6 ln. 3-13).

6. *Throughout the text the authors have written "anterior tibialis" on line 7 and the caption for the supplementary figure one. Could the authors change it to "tibialis anterior"?*

We have changed the label to tibialis anterior throughout the manuscript.

Original Article

Muscle contributions to vertical and fore-aft accelerations are altered in subjects with crouch gait

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1   **Abstract**

2   The goals of this study were to determine if the muscle contributions to vertical and fore-

3   aft acceleration of the mass center differ between crouch gait and unimpaired gait and if these

4   muscle contributions change with crouch severity. Examining muscle contributions to mass

5   center acceleration provides insight into the roles of individual muscles during gait and can

6   provide guidance for treatment planning. We calculated vertical and fore-aft accelerations using

7   musculoskeletal simulations of typically-developing children and children with cerebral palsy

8   and crouch gait. Analysis of these simulations revealed that during unimpaired gait the

9   quadriceps produce large upward and backward accelerations during early stance, whereas the

10   ankle plantarflexors produce large upward and forward accelerations later in stance. In contrast,

11   during crouch gait, the quadriceps and ankle plantarflexors produce large, opposing fore-aft

12   accelerations throughout stance. The quadriceps force required to accelerate the mass center

13   upward was significantly larger in crouch gait than in unimpaired gait and increased with crouch

14   severity. The gluteus medius accelerated the mass center upward during midstance in unimpaired

15   gait; however, during crouch gait the upward acceleration produced by the gluteus medius was

16   significantly reduced. During unimpaired gait the quadriceps and ankle plantarflexors accelerate

17   the mass center at different times, efficiently modulating fore-aft accelerations. However, during

18   crouch gait, the quadriceps and ankle plantarflexors produce fore-aft accelerations at the same

19   time and the opposing fore-aft accelerations generated by these muscles contribute to the

20   inefficiency of crouch gait.

21

1

1 Introduction

2   Many individuals with cerebral palsy walk in a crouch gait pattern characterized by

3   excess hip and knee flexion [1]. Walking in a crouched posture can lead to joint pain [2] and

4   bone deformities [3] and is inefficient [4,5]. Understanding how muscles accelerate the mass

5   center during crouch gait may provide insight about the underlying mechanics and inefficiencies

6   associated with this gait pattern.

7   Previous studies have documented how muscles accelerate the mass center during

8   unimpaired gait [6-8] and have shown that the same muscles that accelerate the mass center

9   upward also modulate fore-aft acceleration [9]. Examining muscle contributions to mass center

10   acceleration can provide insight into the role of individual muscles and the control strategy used

11   during gait. During unimpaired gait, the vasti and gluteus maximus accelerate the mass center

12   upward and backward in early stance, the gluteus medius accelerates the mass center upward in

13   mid stance, and the ankle plantarflexors accelerate the mass center upward and forward in late

14   stance [6-8]. This coordinated muscle activity uses different muscle groups at different periods of

15   stance to efficiently modulate vertical and fore-aft mass center accelerations.

16   How muscles modulate vertical and fore-aft accelerations of the mass center during

17   crouch gait and how these accelerations change with crouch severity is not well understood.

18   Previous work has shown that similar muscles accelerate the mass center upward during the

19   single-limb stance phase of both mild crouch gait and unimpaired gait [10]. However, the role of

20   muscles during the double support phase, when fore-aft accelerations are largest, is not known

21   for crouch gait. The ability of muscles such as the gluteus medius and soleus to extend the hip

22   and knee [11] and accelerate the mass center upward [12] has been shown to decrease in a

23   crouched posture; however, the effect of crouch severity on muscle contributions to mass center

24   acceleration has not been investigated. Alterations in the ability of muscles to generate vertical

1   and fore-aft accelerations of the mass center may change the strategy used to accelerate the mass

2   center during crouch gait and contribute to the inefficiency of this gait pattern.

3   The goals of this study were to determine whether: (1) the magnitude and timing of

4   muscle contributions to vertical and fore-aft accelerations differ between crouch gait and

5   unimpaired gait, and (2) the muscle contributions to vertical and fore-aft accelerations change

6   with crouch severity. To calculate muscle contributions to mass center accelerations we created

7   three-dimensional musculoskeletal simulations of gait for typically-developing children and

8   children with cerebral palsy and varying degrees of crouch gait (Fig. 1). Examining how

9   individual muscles contribute to vertical and fore-aft accelerations can elucidate the mechanics

10   of crouch gait and inform treatment strategies.

11

12   **Methods**

13   Nine children with cerebral palsy were selected from a database of subjects who had

14   undergone motion analysis at Gillette Children's Specialty Healthcare. The selection criteria for

15   the subjects included: (1) a diagnosis of spastic diplegic cerebral palsy, (2) a minimum knee

16   flexion angle during stance greater than 15°, and (3) a tibial and femoral torsion deformity less

17   than 30° [13]. We also required that the subjects did not use an assistive device during the

18   motion analysis and had at least two consecutive force plate strikes. Nine subjects with crouch

19   gait were divided into three groups based on minimum knee flexion angle during stance: 15 - 30°

20   knee flexion was defined as mild crouch gait, 30 - 50° was defined as moderate crouch gait, and

21   50° or larger was defined as severe crouch gait (Table 1).

22   The typically-developing children were selected from a group of subjects who also

23   visited Gillette Children's Specialty Healthcare for motion analysis and whose gait has been

24   previously simulated [7]. Previous studies demonstrated consistent contributions to vertical and

3

1   fore-aft accelerations during gait in typically-developing children; thus, we chose three subjects

2   with an age range similar to the subjects with crouch gait (Table 1).

3   Motion analysis data was collected using a 12-camera system (Vicon Motion Systems,

4   Lake Forest, CA) and a standard marker measurement protocol [14]. Ground reaction forces

5   were measured with four force plates (AMTI, Watertown, MA). All subjects walked barefoot at

6   their self-selected speed. Surface electromyography (EMG) was recorded from the rectus

7   femoris, hamstrings, gastrocnemius, and tibialis anterior (Motion Laboratory Systems, Baton

8   Rouge, LA) for nine of the subjects. The nine subjects who had EMG data available included

9   three typically-developing subjects, three mild crouch gait subjects, one moderate crouch gait

10 subject, and two severe crouch gait subjects. The EMG signals were sampled at 1080 Hz, band-

11 pass filtered between 20 and 400 Hz, rectified, and low-pass filtered at 10 Hz. The magnitude of

12 the EMG signal was normalized for each muscle group from zero to one based on the minimum

13 and maximum values observed during the motion analysis. Since EMG was not available for all

14 subjects, we averaged the processed EMG signals for each group of subjects for comparison to

15 simulated muscle activations.

16   To create dynamic musculoskeletal simulations of gait, we used a musculoskeletal model

17 with 19 degrees of freedom and 92 musculotendon actuators (lower extremities from [15] and

18 torso from [16]). The degrees of freedom in the model included three translations and three

19 rotations of the pelvis, a ball-and-socket joint between the pelvis and the torso located at the third

20 lumbar vertebrae, ball-and-socket joints at each hip, a custom joint with coupled translations and

21 rotations at each knee, and a revolute joint at each ankle. This model has previously been used to

22 model typically-developing children [7,9] and children with cerebral palsy [10,11,17]. The

23 model was scaled according to anthropometric measurements for each subject using OpenSim

24 [18]. We scaled the maximum isometric force of all muscles by height-squared [19].

4

1   Inverse kinematics, which minimizes the difference between experimental marker

2   trajectories and markers placed on the model, was used to calculate joint angles (Fig. 2A). Joint

3   moments were calculated for each subject using inverse dynamics (Fig. 2B).

4   A dynamic simulation of one gait cycle was generated for each subject. The residual

5   reduction algorithm (RRA) was used to reduce residuals at the pelvis [18]. Residuals are non-

6   physiological forces and moments applied at the pelvis that balance dynamic inconsistencies

7   resulting from experimental errors and modeling assumptions. RRA reduced these residuals by

8   making small changes to measurements that may have experimental error including the position

9   of the torso mass center (changes were less than 2 cm in magnitude) and the kinematics (changes

10   were less than 2° for all joint angles). Using the adjusted model and kinematics determined from

11   RRA, the computed muscle control algorithm (CMC) was used to estimate the muscle forces

12   required to track each subject's kinematics [20,21]. At each time step, CMC determines the

13   distribution of muscle activations, such that model accelerations match the experimental

14   accelerations for all degrees-of-freedom. The algorithm accounts for muscle activation and

15   contraction dynamics, which includes the muscle force-length-velocity relationship. The

16   distribution of muscle activations was determined by minimizing the sum of squared activations

17   at each time step. The estimated muscle activations from CMC were qualitatively compared to

18   the average EMG signal for each gait pattern; constraints on muscle excitations were used when

19   the simulated muscle activity was inconsistent with the EMG signals.

20   An induced acceleration analysis was used to compute the contributions of individual

21   muscles to vertical and fore-aft mass center accelerations [6,22-24] at each time point of a

22   subject's gait simulation. This analysis solves the model's equations of motion, including foot-

23   floor contact constraint equations, to determine the contributions of gravity, velocity, and each

1   muscle force to the mass center acceleration. The contact constraint equations used in this

2   analysis enforce a rolling without slipping constraint to model the foot-floor interaction [22].

3   Before addressing the research questions posed in this study, we evaluated the accuracy

4   of the musculoskeletal simulations to ensure they recreated the dynamics of gait for the typically-

5   developing children and children with cerebral palsy. The average residual forces and moments

6   applied at the mass center of the pelvis were 9.7 N and 16.5 Nm, less than ten percent of body-

7   weight and body-weight*height, respectively, for all subjects. The on-off timing and magnitude

8   of the simulated activations and electromyography were qualitatively similar (Supp. Fig. 1);

9   however, there were some deviations, such as decreased quadriceps activity during early swing

10   of unimpaired gait and increased gastrocnemius activity during swing of severe crouch gait.

11   These differences had minimal effects on muscle contributions to vertical and fore-aft

12   accelerations of the mass center, since these accelerations are generated predominately during

13   stance.

14   To determine if the muscle contributions to vertical and fore-aft accelerations differed

15   between unimpaired gait and crouch gait, we performed a student's t-test with a significance

16   level of 0.05. To determine if contributions to vertical and fore-aft accelerations changed with

17   crouch severity we used a one-way ANOVA to compare mild, moderate, and severe crouch gait

18   with a significance level of 0.05. To evaluate the relative timing of muscle contributions to fore-

19   aft accelerations we used a covariance analysis which examined if major muscle groups, such as

20   the ankle plantarflexors and vasti, were active at similar times during the gait cycle. To examine

21   the relative magnitude of muscle contributions to fore-aft accelerations we calculated the area

22   under the fore-aft acceleration versus gait cycle curves for major muscle groups. For both of

23   these analyses, we compared unimpaired gait and crouch gait using a student's t-test and mild,

24   moderate, and severe crouch gait using a one-way ANOVA.

Results

The vasti (p = 0.03) and rectus femoris (p = 0.03) produced greater backward acceleration of the mass center and the gastrocnemius (p = 0.02) and soleus (p = 0.047) produced greater forward acceleration of the mass center during crouch gait than unimpaired gait (Fig. 3A). The forward acceleration produced by the soleus increased with crouch severity (p = 0.001). In contrast, the fore-aft accelerations produced by the gluteus medius (p < 0.001) and iliopsoas (p = 0.02) were significantly smaller in crouch gait than in unimpaired gait.

When only gravity was applied to the model, the downward acceleration of the mass center was greater (p = 0.001) in crouch gait than in unimpaired gait (Fig. 3B). In the erect posture of unimpaired gait, skeletal alignment supports a larger portion of body weight and, thus, the downward acceleration of the mass center when only gravity was applied was smaller than in a crouched posture. The contribution of the tibialis anterior to downward acceleration was greater during crouch gait than unimpaired gait; however, muscle contributions to downward acceleration of the mass center were small relative to gravity. The vasti, gastrocnemius, and soleus produced the largest upward accelerations of the mass center during crouch gait and unimpaired gait. The upward acceleration produced by the gluteus medius was significantly less during crouch gait than unimpaired gait (p < 0.001). The upward acceleration produced by the gastrocnemius decreased with crouch severity (p = 0.02).

The forces produced by the vasti (p = 0.04) and rectus femoris (p = 0.01) were significantly greater in crouch gait than in unimpaired gait, and vasti force increased (p = 0.005) with crouch severity (Fig. 3C). The change in vasti force was larger than the change in upward and backward accelerations produced by the vasti because of a diminished capacity of the vasti to accelerate the mass center in a crouch posture (Supp. Fig. 2). For example, vasti force during severe crouch gait increased by 340% compared to unimpaired gait, but the upward acceleration

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1   produced by the vasti only increased by 184% because the upward acceleration produced per

2   newton of muscle force of the vasti decreased by 54% in severe crouch gait.

3   The relative timing and magnitude of the fore-aft accelerations generated by the vasti

4   and gastrocnemius differed between crouch gait and unimpaired gait, as indicated by changes in

5   the covariance and area under the fore-aft acceleration curves (Fig. 4). In unimpaired gait, the

6   vasti accelerated the mass center upward and backward during early stance and the ankle

7   plantarflexors accelerated the mass center upward and forward during late stance. The

8   covariance of the fore-aft accelerations generated by the vasti and gastrocnemius during

9   unimpaired gait was close to zero (-0.08 ± 0.03), indicating that these muscles were active at

10   different times of the gait cycle. During crouch gait, the vasti and ankle plantarflexors both

11   contributed to fore-aft accelerations throughout stance, resulting in large, opposing fore-aft

12   accelerations. The covariance of the fore-aft accelerations generated by the vasti and

13   gastrocnemius was -0.71 ± 0.14 during crouch gait, significantly different than unimpaired gait

14   (p = 0.03), indicating that these muscles were active at the same time and accelerated the mass

15   center in opposite directions. Additionally, the areas under the fore-aft acceleration curves of the

16   vasti (p = 0.01) and gastrocnemius (p = 0.02) were significantly greater in crouch gait than in

17   unimpaired gait due to these muscles' sustained contributions to fore-aft accelerations during

18   crouch gait.

19

20   **Discussion**

21   As in unimpaired gait, two muscle groups, the quadriceps and ankle plantarflexors, were

22   largely responsible for accelerating the mass center upward and modulating fore-aft acceleration

23   during crouch gait. However, unlike unimpaired gait, these muscles contributed to mass center

24   accelerations throughout stance and produced large, opposing fore-aft accelerations. During

25   crouch gait, the ankle plantarflexors accelerated the mass center upward and forward while the

1   vasti accelerated the mass center upward and backward throughout stance. In unimpaired gait,

2   individuals modulate speed by increasing or decreasing quadriceps and ankle plantarflexor

3   muscle activation proportionally across the gait cycle [7]. The sustained and opposing fore-aft

4   accelerations generated by the quadriceps and ankle plantarflexors during crouch gait limit the

5   effectiveness of this mechanism to modulate speed.

6   A crouched posture increases the demand on muscles to accelerate the mass center

7   upward due to a decrease in skeletal support and an increase in the knee extensor moment. The

8   quadriceps and ankle plantarflexors produce the greatest upward acceleration of the mass center

9   during crouch gait, but the gluteus medius' ability to accelerate the mass center upward is

10   significantly reduced compared to unimpaired gait [12]. During unimpaired gait, the gluteus

11   medius accelerates the mass center upward in mid-stance during the transition from quadriceps

12   to ankle plantarflexors activity. During crouch gait, the gluteus medius contribution to upward

13   acceleration is reduced and a different strategy is needed to support the mass center in mid-

14   stance. Furthermore, the upward acceleration produced per newton of muscle force decreases

15   with crouch severity for both the quadriceps and ankle plantarflexors [11] and other muscles may

16   need to be recruited to accelerate the mass center upward. Previous experimental studies have

17   also reported increased quadriceps demand [25,26] and prolonged ankle plantarflexor activity

18   during crouch gait [27].

19   Understanding how muscles contribute to vertical and fore-aft accelerations can assist in

20   evaluating treatment options. Demand on the vasti and rectus femoris was greater during crouch

21   gait and may contribute to fatigue. Strength training or other programs that improve the

22   endurance of these muscles may improve the overall endurance of individuals with crouch gait.

23   The ankle plantarflexors were also critical muscles for accelerating the mass center upward and

24   forward during crouch gait and may be targets for strength training programs. Engsberg et al.

1 (2006) reported an improvement in knee flexion during stance after strengthening the ankle

2 plantarflexors [28]. Similarly, ankle foot orthoses may assist the ankle plantarflexors and

3 improve the efficiency of crouch gait [29,30]. From a surgical perspective, weakening or

4 reducing the force-generating capacity of the gastrocnemius or soleus by musculotendon

5 lengthening, neuromuscular toxins, or other procedures could reduce an individual's ability to

6 accelerate their mass center upward or forward.

7 Simulation enables analysis of the accelerations produced by muscles; however, there are

8 limitations to these methods. The models used in this study were scaled from adult models and

9 may not reflect bone deformities or altered muscle physiology of individuals with cerebral palsy.

10 We excluded subjects with significant bone deformities. However, measurements of how muscle

11 physiology changes in individuals with cerebral palsy are needed to incorporate the effects of

12 contracture, spasticity, and other pathologies. These changes in muscle physiology would not

13 affect the direction of the vertical or fore-aft accelerations produced by each muscle, but could

14 affect the relative magnitude of force produced by different muscles. Estimated muscle

15 activations were compared to EMG; however, EMG data was available from a few muscles in a

16 subset of the subjects and only from one of the subjects in the moderate crouch gait group.

17 Although the estimated activations were similar to EMG during stance, when muscles

18 predominately contribute to mass center accelerations, the EMG data was noisy and varied

19 between subjects. Furthermore, to estimate muscle activations we minimized the sum of squared

20 muscle activations, but recognize that other cost-functions may be more appropriate for

21 simulating pathologic gait. EMG from more muscle groups and analysis of other cost-functions

22 could improve future simulations. This study also had a limited number of subjects which may

23 not be representative of the larger population and may not have provided the power to detect

24 some differences in muscle contributions to mass-center accelerations. We have made the

1 simulations included in this study freely available on-line for other researchers to evaluate and

2 use for future research (https://simtk.org/home/crouchgait).

3   By creating musculoskeletal simulations of individuals with cerebral palsy and crouch

4 gait, we have determined that a different strategy is used to accelerate the mass center during

5 crouch gait. The quadriceps and ankle plantarflexors are the primary muscle groups that

6 accelerate the mass center upward; however, sustained activity of these muscles during stance

7 produces large, opposing fore-aft accelerations – like driving with your parking brake on. Future

8 studies that examine the metabolic costs of crouch gait and explore why individuals adopt a

9 crouch gait pattern will be critical for improving treatment and quality of life. Examining how

10 individual muscles contribute to gait using musculoskeletal simulation provides a foundation for

11 these future studies and a basis for clinicians and researchers to understand the underlying

12 mechanics of gait pathologies.

13

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Table 1: Subject characteristics (average ± standard deviation)

	N	N (with EMG)	Age (years)	Height (cm)	Mass (kg)	KFA* (deg)
Unimpaired	3	3	10 ± 3	144 ± 16	36 ± 9	-2 ± 4
Mild Crouch	3	3	9 ± 1	124 ± 10	24 ± 4	18 ± 2
Moderate Crouch	3	1	11 ± 2	136 ± 6	43 ± 31	34 ± 2
Severe Crouch	3	2	14 ± 2	157 ± 12	41 ± 8	64 ± 20

* KFA: Minimum knee flexion angle during stance

Figure Captions

Figure 1. Musculoskeletal model of an individual with cerebral palsy and crouch gait. Vertical and fore-aft accelerations of the mass center were calculated by analyzing muscle-driven simulations.

Figure 2. Average hip, knee, and ankle flexion angles and moments during unimpaired gait and mild, moderate, and severe crouch gait. The joint moments are normalized by body mass (kg).

Figure 3. The average (A) fore-aft and (B) vertical accelerations of the mass center during stance produced by each muscle and (C) the average muscle force during stance normalized by body weight (BW). Error bars are ± 1 standard error. A '*' indicates a significant difference ($p < 0.05$) in the student's t-test comparing unimpaired gait and crouch gait. An arrow indicates a significant change with crouch severity ($p < 0.05$) from a one-way ANOVA comparing mild, moderate, and severe crouch gait. In (B), 'Gravity' indicates the acceleration of the mass center when only gravity is applied to the mass center. The vertical acceleration provided by skeletal alignment is equal to 9.81 m/s^2 minus 'Gravity.'

Figure 4. The fore-aft accelerations of the mass center produced by the vasti (gray line) and gastrocnemius (black line) during stance. The gray area shows the experimentally measured acceleration of the mass center (fore-aft ground reaction force normalized by body mass).

Supplementary Figure 1. Average ± 1 standard deviation of the EMG signal of each group (gray) and estimated muscle activations for each subject (black lines) from the quadriceps, hamstrings, gastrocnemius, and tibialis anterior during unimpaired gait and mild, moderate, and severe crouch gait. Only one individual with moderate crouch gait had EMG, thus we took the average of multiple gait cycles. The magnitude of the EMG and activations were normalized from 0 to 1 based upon the minimum and maximum values during the gait cycle. The bars at the top of each graph indicate when a muscle was constrained to be on (filled bar) or off (open bar) for each subject. Constraints were applied by specifying a minimum ($0.15 - 0.25$) or maximum (0.05) value for the activation during the time periods when the muscle was constrained to be on or off, respectively.

Supplementary Figure 2. The average (A) fore-aft and (B) vertical accelerations produced per 1 newton of muscle force during stance of each muscle. Error bars are ± 1 standard error. A '*' indicates a significant difference ($p < 0.05$) in the student's t-test comparing unimpaired gait and crouch gait. An arrow indicates a significant change with crouch severity ($p < 0.05$) from a one-way ANOVA comparing mild, moderate, and severe crouch gait.
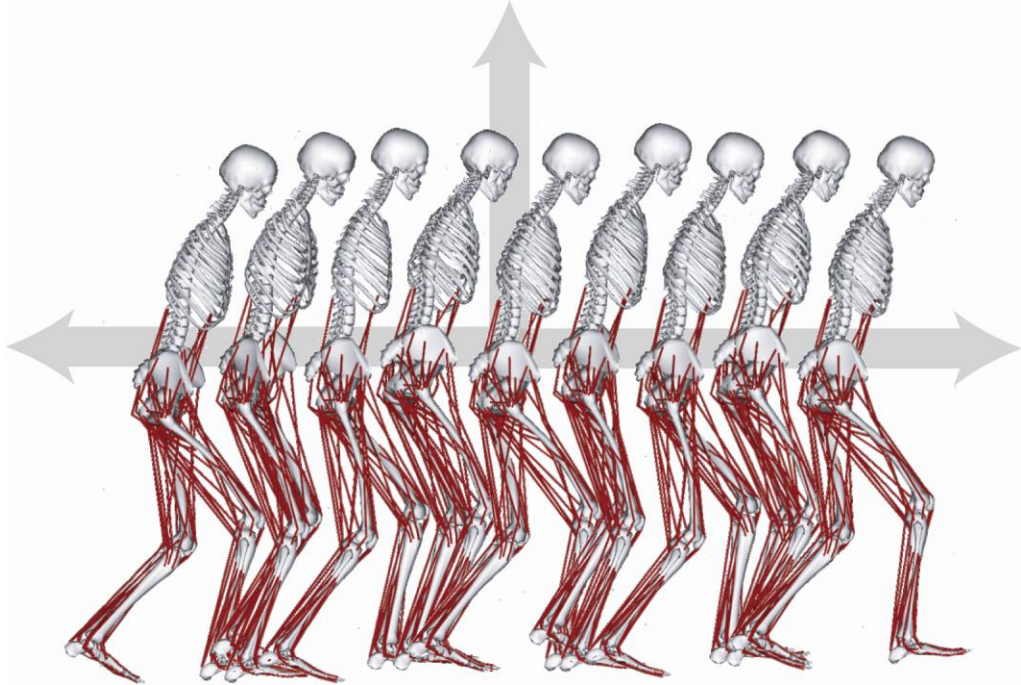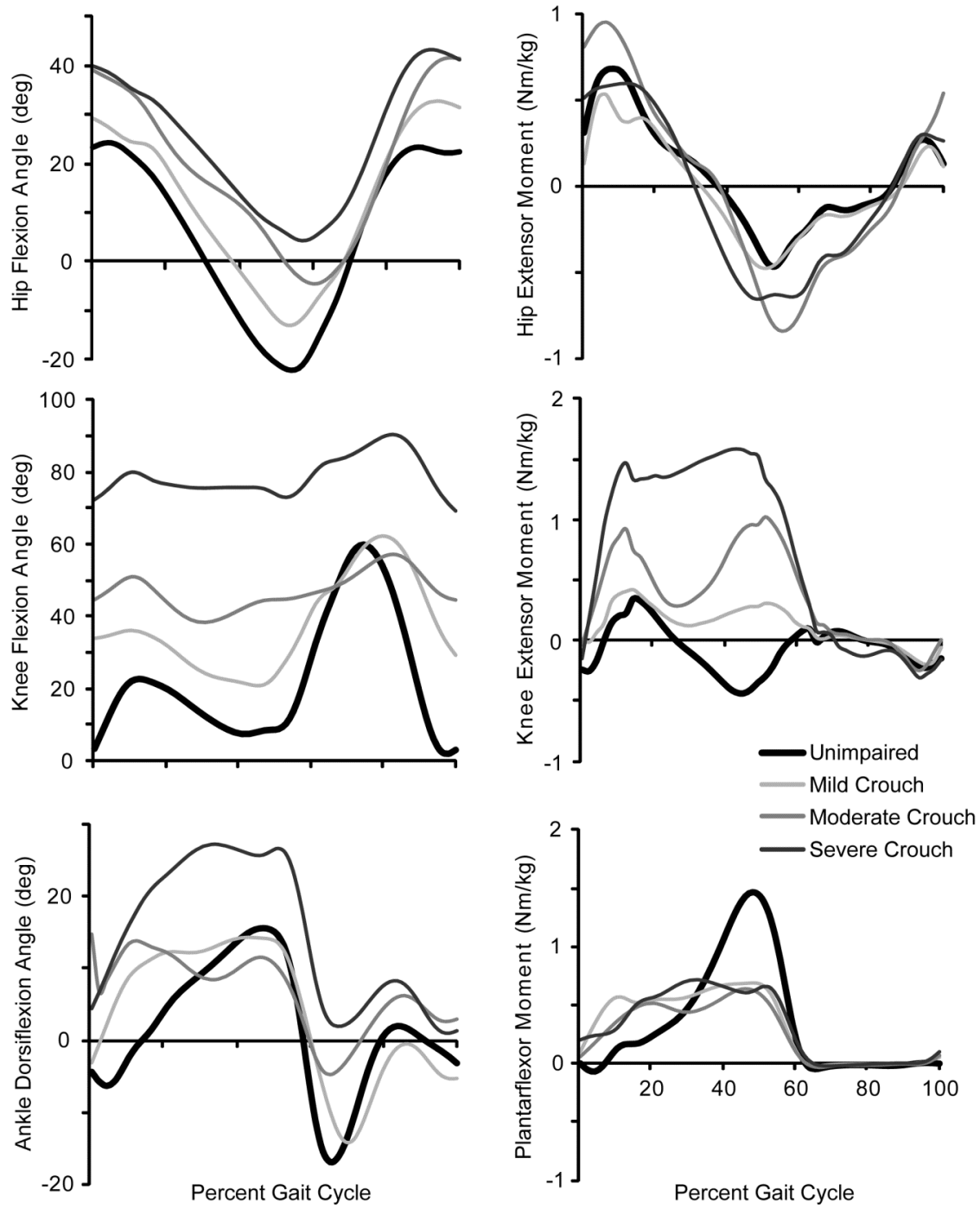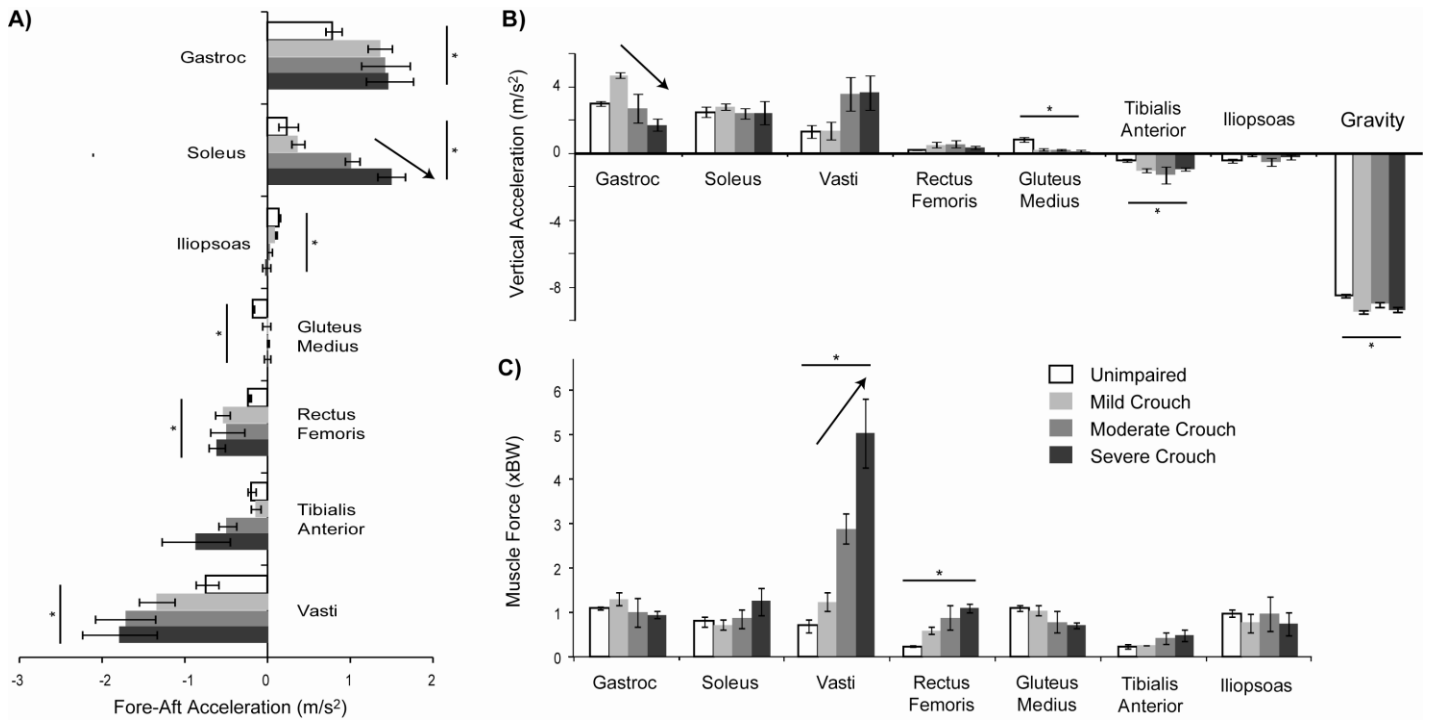
Figure 1

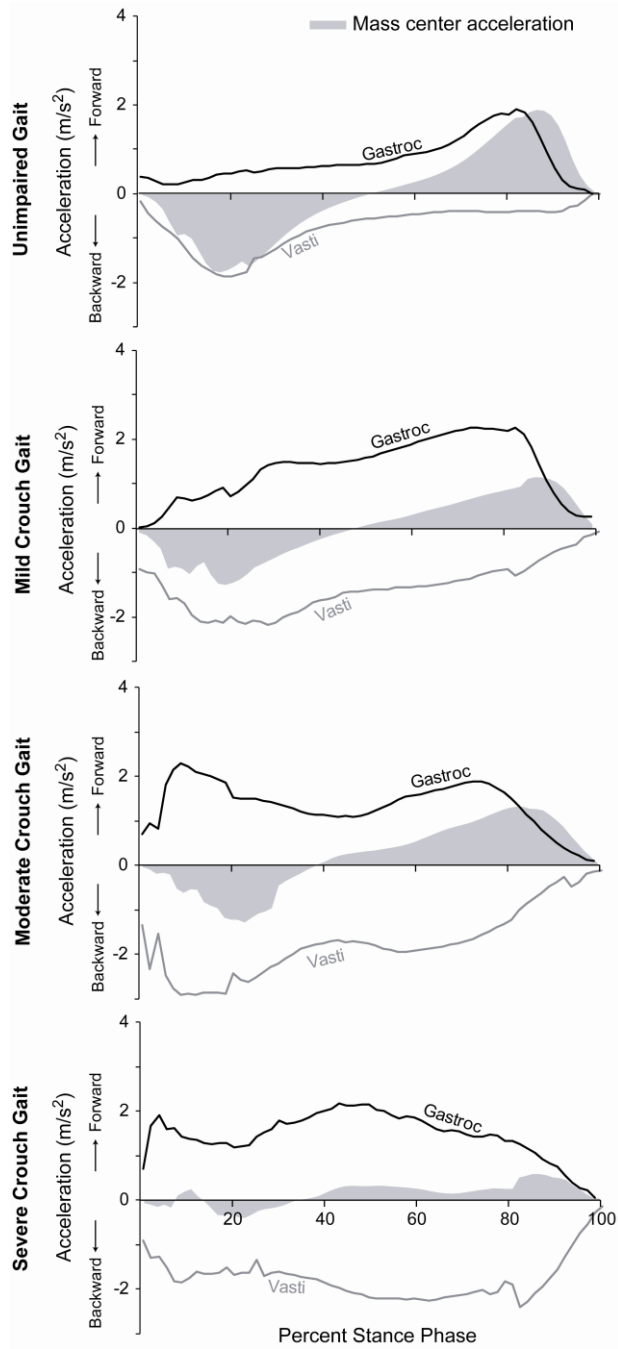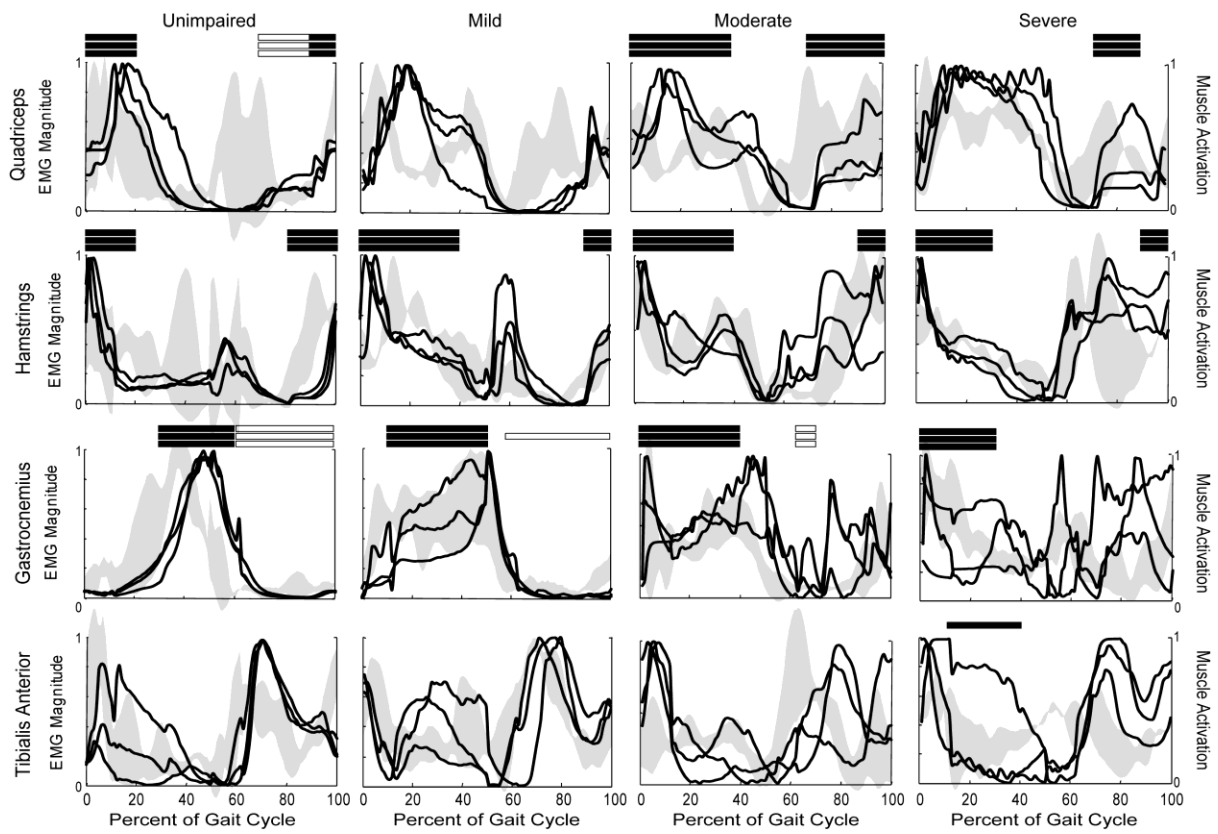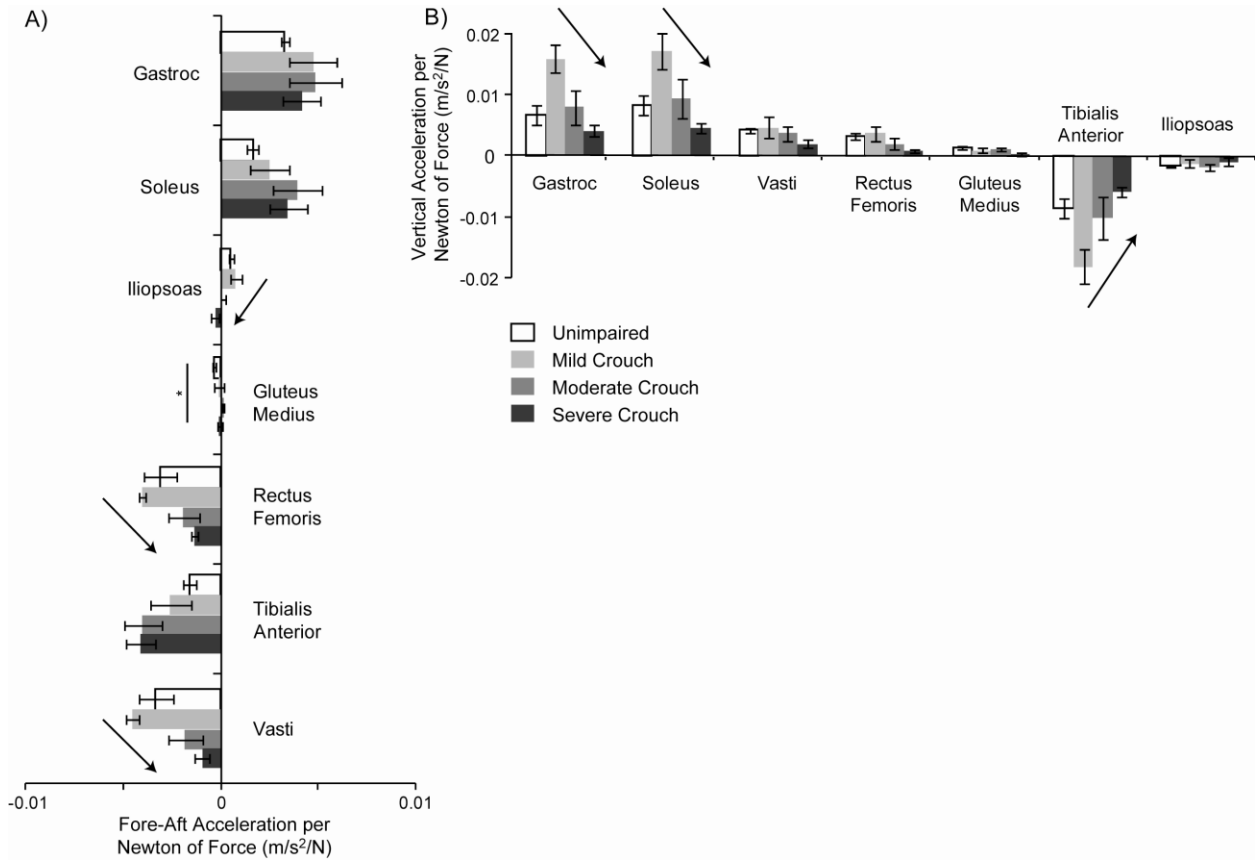**Figure 2**

Figure 3

Figure 4

Supplementary Figure 1

Supplementary Figure 2

Research Highlights

1. We created simulations of crouch gait in individuals with cerebral palsy.
2. In crouch gait, the ankle plantarflexors and vasti accelerate the mass center up.
3. The ankle plantarflexors and vasti produce large, opposing fore-aft accelerations.