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Dissipation of disturbances seen in the knee joint kinematics of children with cerebral palsy

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Purpose: Children with cerebral palsy (CP) often use a crouch gait pattern that has disturbances in the knee joint kinematics. Although the length and rate of lengthening of the hamstring musculature have been speculated to be the reason that these disturbances are not adequately dissipated, this relationship has not been adequately explored. The purpose of this exploratory investigation was to use simulations of a musculoskeletal model and Floquet analysis to evaluate how the performance of hamstrings musculature during gait may be related to the knee joint instabilities seen in children with CP. Methods: Children with CP and typically developing (TD) children walked on a treadmill as a motion capture system assessed the knee joint kinematics. Floquet analysis was used to quantify the rate that disturbances present at the knee joint were dissipated, and simulations of a musculoskeletal model were used to estimate the *in vivo* length and velocity of the hamstrings. Pearson correlation coefficients were calculated to determine if there was a relationship between the rate that the disturbances were dissipated and the performance of the hamstring musculature. Results: The children with CP had hamstrings that lengthened more slowly than TD children, and required more strides to dissipate disturbances in the knee joint kinematics. There was negative correlation between the rate that the hamstrings lengthened and the rate that the knee joint disturbances were dissipated. Conclusions: Our results suggest that the ability of children with CP to dissipate the knee joint disturbances may be related to the inability to properly control the hamstring musculature.

Key words: *walking, gait, crouch, variability, biomechanics, musculoskeletal model*

1. Introduction

Almost 3.5 out of every 1000 children born in the United States have cerebral palsy (CP), which results from a defect or insult to the immature developing brain [20]. Although the brain insult does not progressively worsen, there is often an accumulation of musculoskeletal and sensory impairments that limit the child's mobility. Children with CP who are classified as spastic diplegic often select to use a crouch gait pattern that is characterized by excessive flexion of the hip, knee and ankle during the stance phase [8], [18]. Although the crouch can be promoted from a number of musculoskeletal impairments, the length and control of the hamstring musculature are largely cited as primary factors [2], [4], [8], [11]. The impaired control of the hamstring musculature not only encourages the crouch, but has also been speculated to create disturbances in the knee joint kinematics that can impact the child's overall walking balance [5], [8], [18]. Although this seems plausible, there still is a large gap in our understanding of how the *in vivo* performance of the hamstring musculature influences the ability of children with CP to dissipate the disturbances seen in the knee joint kinematics.

Within the last decade, musculoskeletal modeling and simulations have emerged as the premier biomechanical tool for the assessment of lower extremity muscle function and performance during movement [2], [3], [16], [17], [19]. By generating simulations of walking, it is possible to determine how the forces of

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individual lower extremity muscles contribute to the body's acceleration during gait. Moreover, these modeling efforts have proven to be a valuable clinical tool for making estimations of the *in vivo* length and rate of change of the hamstring musculotendenous units [2], [3], [19]. Outcomes from the simulations of these models have shown that the length of the hamstrings may not always be the factor that promotes the crouch gait in children with CP [2],[3]. In addition, other simulations have shown that children who utilize a crouch gait may have slower rates of change of the hamstring musculotendenous unit during the terminal portion of the swing phase due to spasticity [2], [19]. It has been suggested that this spasticity may limit the child's ability to walk with a more upright position. Overall, these musculoskeletal models have provided innovative insight on the performance of the lower extremity musculature in children with CP. However, simulations from these models have yet to be used to evaluate how the performance of the hamstring musculature may limit the ability of children with CP to dissipate disturbances that are present in the knee joint kinematics.

The field of dynamic systems has a rich history in the application of nonlinear analysis tools for the assessment of the stability of movement patterns based on the rate of change of a set of state variables, such as the angular positions and derivatives of the lower extremity joints. Experimental data has shown that the state variables that define the joint kinematics typically oscillate in a rhythmic pattern and form a closed loop trajectory or limit cycle (Fig. 1) [9]. Assessing how disturbances in the movement pattern influence the ability to return back to the limit cycle trajectory has proven to be rewarding in the assessment of the stability of movement patterns seen in humans, animals, and walking robots [7], [9], [10], [13], [14]. Overall, these studies have shown that a movement pattern is less stable if it takes more strides to return back to the limit cycle trajectory.

Floquet analysis is a well-established technique that has been used to quantify how disturbances influence the rate that the movement pattern returns back to the limit cycle trajectory [7], [9], [10], [13], [14]. These disturbances may arise from improper timing in the activation of the muscles, mechanical instabilities in the joint couplings, or noise in the nervous system. This methodology uses Poincare sections of the limit cycle attractor to evaluate if disturbances present in the movement pattern grow or decay away from the limit cycle (Fig. 1b and c). The movement pattern is considered to be more readily able to dissipate disturbances present in the joint kinematics if it is capable of returning back to the limit cycle trajectory at a faster rate. The largest Floquet multiplier (λ) has the greatest influence on the system's dynamics and quantifies the rate of dissipation of the disturbances [7],[9]. If λ is closer to zero, then it takes fewer strides to dissipate the disturbances, and to return back to the preferred limit cycle trajectory. Alternatively, if the λ is further away from zero, it takes more strides to dissipate the disturbances.

The aim of this exploratory investigation was directed at identifying if the performance of the ham-

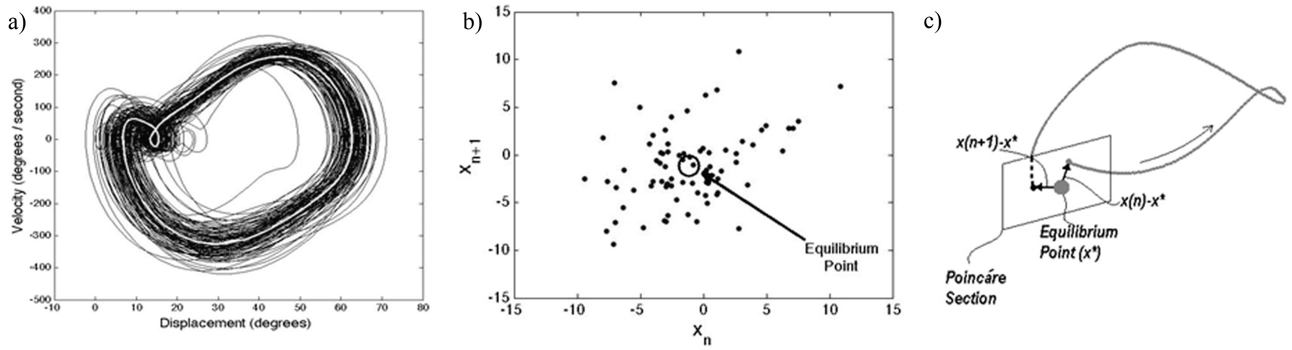

Fig. 1. Graphical depiction of the Floquet analysis. (a) Representative limit cycle attractor for the knee joint. The state variables of the walking kinematics are used to construct the attractor, which has a limit cycle shape. The attractor is constructed by plotting the angular position on the abscissa and the angular velocity on the ordinate; (b) An exemplary Poincare section of the knee joint attractor shown. A Poincare section represents the state of the system at one point in the attractor. The section is created by plotting the state of the system at X_n versus X_{n+1}. For this particular Poincare section, X_n represents the knee joint angle at the nth heel-contact, and X_{n+1} represents the next consecutive knee joint angle at heel contact. Disturbances in the knee joint promote the trajectories to diverge away from the preferred equilibrium or stable point of the knee joint pattern; (c) Three dimensional depiction of the attractors, where the bold line represents the limit cycle and the plane represents a Poincare section. The Poincare sections are used to evaluate the amount of divergence or convergence in the knee joint pattern from the equilibrium point one stride ($X(n)–X^*$) to the next ($X(n + 1)–X^*$). X^* is the equilibrium point, which is determined from the mean limit cycle trajectory in the Poincare section

string musculature is related to the rate that the disturbances present in the knee joint kinematics of children with CP are dissipated. To this end, we used simulations from a musculoskeletal model to simulate the performance of the hamstrings during gait. These simulations were used to predict the *in vivo* changes in the hamstring length and rate of change during gait. In addition, we employed methods from Floquet analysis to quantify the rate that the disturbances seen in the knee joint are dissipated, and correlated the rate that these disturbances are dissipated with the outcomes of our musculoskeletal simulations.

2. Materials and methods

Participants

The University Institutional Review Board approved all experimental procedures, and the parents consented and the children assented to participating in the experiment. Eight children with spastic diplegic CP (age = 9.6 $\pm$ 2 yrs), and six typically developing (TD) children (age = 8.8 $\pm$ 2 yrs) participated in this exploratory investigation. The children with CP had a Gross Motor Function Classification System level between I or II, and wore their prescribed ankle-foot orthosis during the experiment. We selected to have the children walk in their ankle-foot orthosis in order to ensure that the walking patterns exhibited by the children during our experiment represent how they normally walk in the community. Additionally, the children with CP were classified as having a crouched gait since they had a knee joint angle of 30.6 $\pm$ 8 degrees at heel-contact and a popliteal angle of 43 $\pm$ 9 degrees.

Experimental Methods

Children walked on a treadmill for two minutes at 0.8 m/s. The 0.8 m/s speed was selected based on previously reported average walking speeds for children with cerebral palsy [1]. A three-dimensional motion capture system (120 Hz) was used to track a modified Helen Hayes reflective marker set that was placed on the participant's lower extremities. A knee alignment device (KAD) was used during the standing calibration to ensure that the markers were correctly aligned with the underlying boney structure. The position data for all markers were filtered using a zero-lag fourth order Butterworth filter with a 6 Hz cut-off, and the Vicon plug-in gait software (Vicon, Centennial, CO) was used to calculate the knee joint sagittal plane angles. The respective derivatives were determined using the first-central difference method.

Floquet analysis

A state vector (S) was created to define the knee joint attractor dynamics (equation (1))

$$S(t) = [\theta, \dot{\theta}] \quad (1)$$

where θ represented the sagittal plane knee joint angle and $\dot{\theta}$ was the respective derivative. We evaluated the sagittal plane joint kinematics because the primary influence of the hamstrings is in the sagittal plane.

The state space data were partitioned into their respective strides based on the maximum forward displacement of the ankle marker, and were normalized to 101 samples using a cubic spline routine. Subsequently, Poincare maps were created for every sample of the normalized stride (equation (2))

$$\mathbf{S}_{n+1} = \mathbf{F}(\mathbf{S}_n) \quad (2)$$

where **S** is the state vector of the system, **F** is the function that describes the change in the location of the state vector in the Poincare map from one stride (n) to the next (n + 1). For example, if the knee joint pattern was completely periodic (i.e., no deviation from the preferred joint kinematics), the function would map to the same point in Poincare map. However, this is not the case because the joint kinematics fluctuates slightly from stride-to-stride.

It was assumed that the mean ensemble (S^*) represented the preferred joint kinematics, and deviations away from this mean from one stride (S_n) to the next (S_{n+1}) represented disturbances (equation (3))

$$[S_{n+1} - S^*] = J(S^*)[S_n - S^*]. \quad (3)$$

The rate of change in the state vector from one stride (n) to the next (n + 1) was quantified by the Jacobian ($J(S^*)$). A least squares algorithm was used to solve for the Jacobian, and the Floquet multipliers were the eigenvalues of the Jacobian [9]. For each child's gait, the λ was calculated for each point of the normalized stride. The λ from all the points of the normalized stride was used to quantify the dissipation rate of the disturbances present in the knee joint kinematics. A λ that was further away from zero signified that it took more strides to dissipate the disturbances that were present in the knee joint kinematics [9], [7].

Musculoskeletal simulations

Similar to previous investigations, the semimembranosus (SEM) was used to assess the lengthening properties of the hamstrings musculature [2], [3], [19].

The open SIM musculoskeletal modeling software was used to estimate the *in vivo* SEM's musculotendon lengthening properties [6]. The simulations were driven by each child's gait kinematics which were quantified during the motion capture session. The calculated musculotendon lengths were filtered using a zero-lag fourth order Butterworth filter with an 8 Hz cut-off, and were differentiated to calculate the rate that the SEM lengthened. We normalized the SEM musculotendon length and lengthening velocity based on the average length and rate of lengthening, respectively [2]. The maximum of the SEM length and velocity during the terminal portion of the swing phase were used to quantify the length and rate of lengthening of the SEM.

Statistical analysis

Independent *t*-tests were used to discern difference between the respective groups for the λ, length of the SEM, and rate that the SEM lengthened. In addition, a Pearson product moment correlation was used to determine if the λ for the children with CP was significantly correlated with the rate that the SEM lengthened. All statistical analyses were performed at an alpha level of 0.05, and the results are presented as mean $\pm$ standard error of the mean.

3. Results

Figure 2 depicts the simulated length and lengthening rate of the SEM musculotendonous unit throughout the gait cycle for the respective groups. There was no difference in the length of the SEM musculotendon unit at the terminal portion of the swing phase between the two groups (CP = 1.05 $\pm$ 0.01; TD = 1.06 $\pm$ 0.01;

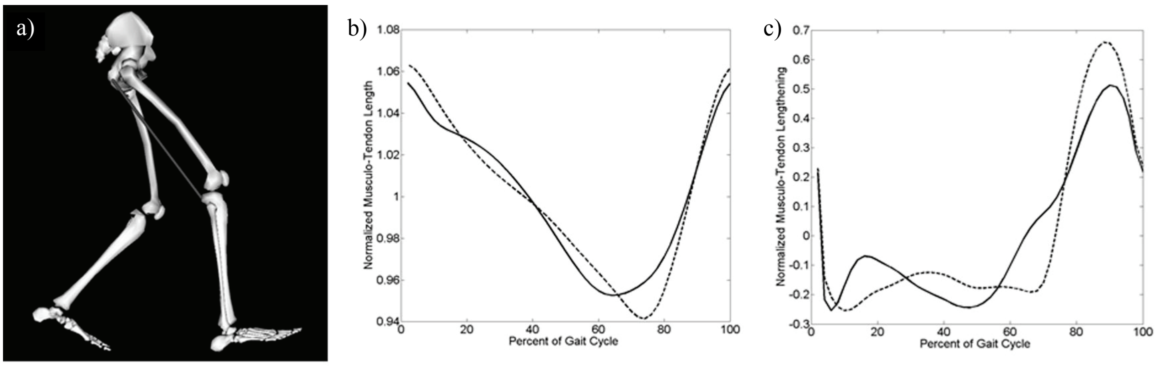

Fig. 2. (a) Depiction of the musculoskeletal model that was used to simulate the change in the length of the semimembranosus based on the subjects walking kinematics [6]; (b) Average group simulation results of the length of the semimembranosus musculotendonous unit throughout the gait cycle; (c) Average group simulation results of the rate of change of the length of the semimembranosus musculotendonous unit throughout the gait cycle. Simulation results from the children with cerebral palsy are presented as a solid line, and the results from the typically developing children are presented as a dashed line

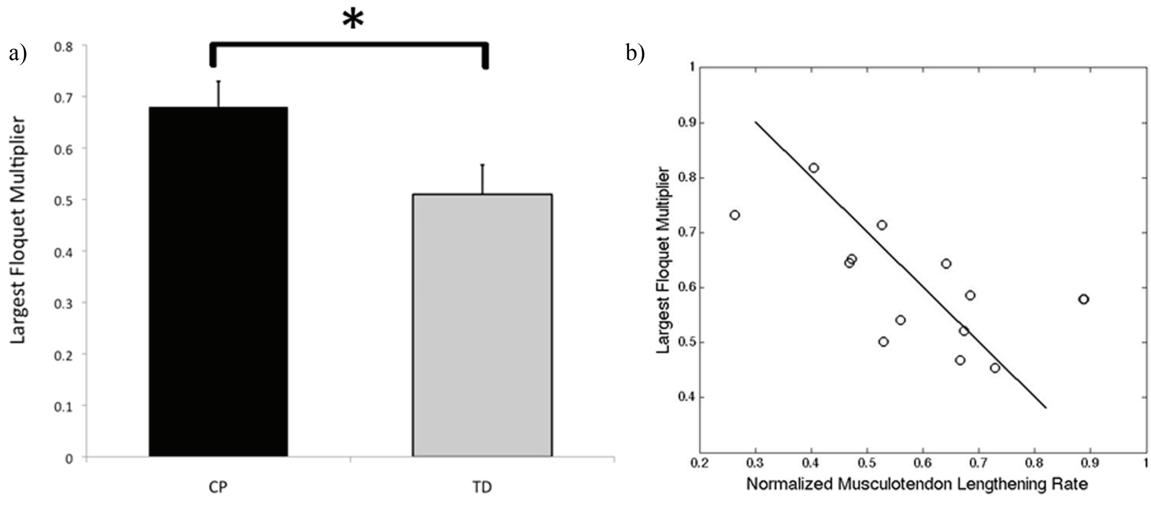

Fig. 3. (a) Mean $\pm$ standard error of the mean for the knee joint maximum Floquet multipliers (λ) for the children with cerebral palsy (CP) and the typically developing children (TD). * $p < 0.05$. The larger the λ the more strides it would take to dissipate disturbances in the knee joint kinematics; (b) Plot of the relationship between the semimembranosus musculotendon lengthening rate and λ

p = 0.11). Hence, indicating that the SEM musculotendon unit achieved a similar length for both groups. Despite achieving the same length, there was a difference in the lengthening rate of SEM musculotendon unit during the terminal portion of the swing phase, with the children with CP having a slower lengthening rate than the TD children (CP = 0.49 $\pm$ 0.09; TD = 0.66 $\pm$ 0.05; $p < 0.0001$).

The largest Floquet multiplier for the knee joint was greater for the children with CP (CP = 0.68 $\pm$ 0.14; TD = 0.51 $\pm$ 0.14; $p = 0.02$; Fig. 3), indicating that the children with CP required more steps to dissipate the local disturbances that were present in the knee joint kinematics. Additionally, there was a negative correlation between the lengthening rate of SEM musculotendon unit, and the λ calculated for the knee joints of the children with CP ($r = -0.62$; $p = 0.05$; Fig. 3). The negative relationship indicated that children with CP who have a slower lengthening rate require more strides to dissipate the disturbances in their knee joint kinematics.

4. Discussion

We investigated the relationship between performance of the hamstring musculature and the dissipation of disturbances seen in the knee joint of children with CP who walk with a crouch gait. Our experimental approach was novel in that we used simulations from a musculoskeletal model to predict the *in vivo* performance of the hamstrings musculature combined with Floquet analysis to quantify how the disturbances seen in knee joint kinematics were dissipated across the strides. Overall our results show that the control of the hamstring musculature during the terminal portion of the swing phase is related to the ability of children with CP to dissipate the disturbances that are present in their knee joint kinematics.

The magnitude of the λ for the knee joint was greater for the children with CP compared with the TD children. This indicates that children with CP require more strides to dissipate the disturbances that are present at the knee joint. The crouch gait has previously been suggested to be an alternative movement strategy that children with CP adopt to improve their walking balance [5]. Contrary to this logic, our results suggest that the crouched gait may not be an effective strategy for improving the walking balance because it is related to a reduced ability to dissipate disturbances that are present in the knee joint kinematics. Potentially, orthotic interventions and/or surgical techniques that are directed at improving the performance of knee joint may improve the ability of children with CP to dissipate the disturbances seen in the knee joint kinematics

The musculoskeletal simulations employed in this investigation were used to infer how the *in vivo* performance of the hamstring musculature influenced the knee joint kinematics. Similar to previous investigations, our simulations also showed that the hamstrings of the children with CP that had a crouch gait achieved the same length as the TD children [2], [3], [5]. These results provide further support for the notion that the length of the hamstrings may not be the cause of the crouched gait seen in children with CP. On the other hand, the simulations revealed that the hamstrings of the children with CP were lengthening at a slower rate during the terminal portion of the swing phase. Prior investigations have shown that a slower lengthening rate provides a way to quantify the influence of muscular spasticity during gait [2], [3]. Therefore, it is plausible that spasticity present in the hamstrings may be one of the factors that were promoting the crouch gait of the children in our study. Further studies are warranted to establish the link between the rate of change of the hamstring musculature in the simulations and clinical measures that quantify the degree of spasticity present in the hamstrings (e.g., Ashworth scale).

The magnitude of the λ was negatively correlated with the lengthening rate of the hamstring musculature predicted from the simulations. This indicated that the children with CP who required more strides to dissipate the disturbances tended to also have a slower hamstring lengthening rate. This relationship provides further support for the impression that the instabilities seen in the knee joint of the crouch gait may be partially due to a lack of control of the antagonist muscles during the terminal portion of the swing phase. Since the hamstring lengthening rate has been proposed as a dynamic measure of spasticity during gait [3], we speculate that spasticity may have created the instabilities and/or limited the ability of the children with CP to dissipate the disturbances present in the knee joint kinematics. There is growing evidence that Botulinum toxin type A (Botox) therapy can decrease the spasticity of the lower extremity musculature and improve the gait of children with CP [11]. In addition, a recent study that used simulations from a musculoskeletal model has shown that Botox therapy can improve the length and lengthening rates of the lower extremity musculature in adults who have incurred a stroke [12]. We suspect that Botox therapy may also have a similar effect on the hamstring musculature of children with CP, which may improve the ability of children with CP to dissipate the disturbances that may be present in the knee joint kinematics. Further studies that use the methods employed in this investigation are warranted to establish the efficacy of the current treatment approaches that are used to improve the ability of children with CP to dissipate such disturbances.

5. Conclusions

Our exploratory results suggest that children with CP that have a crouch gait appear to require more strides to dissipate the disturbances that are present in the knee joint kinematics. The simulations from a musculoskeletal model also suggest that the rate that the disturbances are dissipated may be related to the control of the hamstring musculature during the terminal portion of the swing phase. Future investigations that combine simulations of musculoskeletal models with Floquet analysis might provide new insights on how the *in vivo* muscular performance influences the ability of children with CP to dissipate disturbances that are present in the lower extremity joint kinematics.

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