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MUSCLE SYNERGY DURING A SINGLE LEG STANDING TEST IN AMBULATORY CHILDREN WITH CEREBRAL PALSY

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THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Education at the University of Kentucky

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ABSTRACT OF THESIS
MUSCLE SYNERGY DURING A SINGLE LEG STANDING TEST
IN AMBULATORY CHILDREN WITH CEREBRAL PALSY

INTRODUCTION: Cerebral Palsy (CP) is a sensorimotor disorder characterized by dysfunctional motor coordination, balance problems, and loss of selective motor control. Motor coordination exhibited as co-contraction, has been subjectively quantified using gait analysis, but recent studies have begun to objectively analyze the amount of co-contraction by collecting electromyography (EMG) data. Center of pressure excursion (COPE) measurements collected during a single leg standing test (SLST) have shown to be more valid measurements of balance in populations with motor disabilities than a SLST alone. A recent study has correlated increased COPE velocity with a lower fall risk as determined by reported fall frequency, suggesting a more objective measure of fall risk. The current study aimed to determine if the fall risk calculated by COPE velocity in children with CP is correlated with co-contraction index value in various muscle synergy groups. It was hypothesized that i) co-contraction index values will differ between high and low fall risk groups, ii) there will be preferential activation of different synergy groups within the high and low fall risk groups, and iii) there will be a negative and direct correlation between COPE velocity and co-contraction index values for all synergy groups. METHODS: Fall risk grouping was determined by average COPE velocity values calculated from previously reported fall frequency groups. Balance ability was determined by COPE measurements during a SLST on a force plate. Muscle synergy groups were determined by common muscle pairings at the hip, knee and ankle. Co-contraction indices were determined from linear envelopes plotted from muscle group EMG data. An independent t-test was run on muscle synergy groups between high and low fall risk groups. Nonparametric Analysis of Variance (ANOVA) and Tukey post-hoc tests were run on the high and low fall risk groups separately to determine differences in co-contraction index value within high and low fall risk groups. A Pearson correlation analyzed COPE velocity and co-contraction index value. RESULTS: No significant differences in muscle synergy between the high and low fall risk groups were found ($p = 0.476, 0.076, 0.064, 0.364$). The ANOVA and Tukey post-hoc tests for high fall risk group found significant differences in co-activation index value between the sagittal hip and frontal hip groups ($p = 0.022$) and sagittal hip and ankle groups ($p = 0.016$). Low fall risk group was found to have significant differences between the sagittal hip and frontal hip groups ($p = 0.038$) and frontal hip and knee groups ($p = 0.012$). Weak and negative correlations were found between COPE velocity and both knee and ankle groups ($r = -0.309, -0.323$, $p = 0.059, 0.050$). Negligible and insignificant correlations were found between frontal hip and sagittal hip synergies and COPE velocity (($r = 0.013, -0.068$, $p = 0.475, 0.367$). CONCLUSION: There is insufficient evidence to claim that muscle group activations are different depending on fall risk grouped by COPE velocity. It is not currently possible to correlate COPE velocity to a specific synergy group recruitment. However, data do suggest that sagittal hip and knee strategies are recruited more than ankle and frontal hip strategies during SLST.

KEYWORDS: Cerebral Palsy, Muscle Synergy, Single Leg Stance, Fall, Center of Pressure Excursion, Electromyography

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CHAPTER ONE: INTRODUCTION

Cerebral Palsy, Co-Contraction, and Balance

Cerebral palsy (CP) is a sensorimotor disorder characterized by abnormal motor development and postural control. Persons affected by cerebral palsy are commonly plagued by motor issues such as spasticity, hypertonia, muscle weakness, ataxia, poor motor control, balance problems and loss of selective motor control.[1,2,25] Motor coordination is related to co-contraction, which is a mechanism to regulate activity of agonist and antagonist musculature in relation to time.[2] Co-contraction of muscle groups has been shown to be beneficial in stabilizing joints and increasing force production,[7,15,31,32] but a study by Unnithan et al.[36] showed that children with CP had systematically higher co-contraction values when compared with typically developing children. Excessive co-contraction in this capacity has been linked to inadequate force production and metabolically wasteful gait during functional tasks and has been hypothesized to be one of the causes for abnormal gait in CP.[32,36] Likewise, in elderly populations with deteriorated balance abilities, increased co-contraction, specifically at the ankle, has been correlated with an increased history of falls.[22]

Similarly, it is apparent that CP patients recruit fewer synergistic muscle groups during gait than typically developing children.[34] This could lead to the increased usage of co-contraction as a compensatory mechanism for lack of muscle strength and coordination in CP populations. However, the specific systems and muscles responsible for the changes seen in the pathological gait of this population are not fully understood.

Gait analysis has been used as a subjective measure of observable co-contraction, but as of 2017, there is still no standard measure of co-contraction.[17] Electromyography (EMG) has been used to assess underlying systems involved in standing balance,[17] but there is still little

understanding of balance specific to the CP populations. EMG assessment of muscle activation during balance tasks will give better insight to intrinsic and reflexive dynamics during standing balance by motor unit activation and co-contraction patterns.

Center of Pressure Excursion and Fall Risk

Center of pressure (COP) is defined as the sum force vector of many ground reaction forces sourcing from every point of contact of a subject's foot[16] and has been a popular measurement when quantifying postural sway and balance abilities. Ideally, the body should be able to recover from perturbations using quick COP transitions, or COP excursions (COPE) that transmit forces in the opposite direction of a fall to accelerate the body and maintain balance. However, it has been shown that subjects with decreased sensory-motor system performance in such anomalies as musculoskeletal disorders, aging, and neurological conditions have a deterioration of the proprioceptive mechanisms that assist in balance abilities as measured by COPE mean displacements, velocity, sway path, sway amplitude, and sway frequency.[16,23,26,28] Similarly, COPE velocity has been shown to detect changes in postural sway due to aging.[19]

Statement of the Problem

COPE measures have been shown to be able to assess changes in balance abilities of other neurological disorders, therefore, it would be feasible that fall risk could be inferred from COPE measurements in cerebral palsy patients with sensorimotor abnormalities. Consistent with this hypothesis, Callahan[3] found that there were significant differences in mean COPE velocity during a single leg standing test (SLST) in subjects with cerebral palsy who were classified as high and low fall risk; subjects with a higher fall risk had a higher COPE velocity. Since COPE velocity is correlated with fall risk in a SLST, understanding muscle activation patterns during this task could shed light on the specific mechanisms of imbalance in the cerebral palsy population.

Purpose

The purpose of the study at hand was to determine if the increased fall risk demonstrated in children with cerebral palsy (as defined by COPE velocity) is correlated with specific activation of defined muscle synergy groups. To estimate the activation of these groups, co-contraction indices were calculated and used as an indication of total co-contraction within those muscle synergy groups. A larger co-contraction index value indicates a higher incidence of concurrent activation of the muscles within the specified synergy group. It was hypothesized that i) co-contraction index values differ between high and low fall risk groups as defined COPE velocity. It was also hypothesized that; ii) there is preferential activation of different synergy groups contained within low and high fall risk groups and iii) there is a negative and direct correlation between COPE velocity and co-contraction index values for all of the synergy groups.

If significant correlations are found, this study could provide a broadened understanding to why individuals with cerebral palsy fall more often than normally developing populations. It could provide supplementary information regarding COPE measurements and determining fall risk more precisely. Likewise, it could aid in physicians' knowledge during assessments to correctly and efficiently eliminate or treat cerebral palsy contractures, and to track post-treatment progress.

CHAPTER TWO: EXPANDED LITERATURE REVIEW

This section will further address topics pertinent to muscle synergy and balance, co-contraction, and COPE.

Muscle Synergy and Balance

Muscle synergy is defined as "the functional coupling of groups of muscles such that they are constrained to act together as a unit"[29] and a "group of muscles activated in synchrony with fixed relative gains and consistent spatial characteristics."[35] Spatiotemporal features of EMG (muscle activity) patterns can represent different postural strategies, as noted by Torres-Oviedo.[35] These patterns are suggested to be representative of different modules (synergies) of motor output across time windows in postural responses.[35] These synergies – or co-contractions – are crucial for postural control, gait progression, and stance support during gait. For example, the muscles active in the stance phase of gait act to first to stabilize the posture by absorbing ground reaction forces, then to propel the body forward into swing phase. In the stance phase, eccentric action of the quadriceps aid in a small knee flexion moment to absorb the shock of initial foot contact, while the eccentric action of the tibialis anterior decelerates the foot to preserve forward progression of the body. Both the quadriceps and tibialis anterior act synergistically to reduce impact forces on the body.

Likewise, muscle strategies are utilized in the control of the center of mass (COM) and center of pressure (COP) during static balance activities. According to Prieto et al.,[23] COP is defined as the location of the summed vertical reaction vector on the surface of a force platform on which the subject is standing. This is not the same as the COM, as COP entails dynamic forces caused by subject movement or regulatory activity of the neural control loops that are involved in balance maintenance[16]. The innate quality of body stability requires that the body's COM

never deviates beyond the support area, and the dynamic COP provides a sort of proprioceptive quality to maintain this condition.[16, 23]

Winter[37] poses a pendulum model of human balance and postural control where the relative positioning of the COM and COP determine the muscle synergy used. When perturbed in the anterior-posterior direction, the COM passes ahead of the COP, making the angular velocity clockwise (negative). To correct this "forward sway," the center of pressure is increased in the anterior position using a plantarflexion moment so that the clockwise velocity is reversed. In anterior-posterior sway during quiet stance, ankle plantar flexors and dorsiflexors synergize to impact posture control.[38] In EMG studies,[27] slow backward and forward sway during quiet stance led to the utilization of an ankle strategy comprised of the soleus, gastrocnemius, and tibialis anterior.

Other studies[4,27,39] question the simple pendulum theory of balance, and instead follow a more complex dual coordination pattern between the hip and ankle during stance. Winter[37] addresses the event in which the ankles are not available to contribute to stabilization of body position by using a hip strategy. In this strategy, a hip loading-unloading mechanism is used to adjust the COM to a manageable position. The limitation here is that this mechanism relies on a bilateral stance, as the loading-unloading method does not apply to single leg stance. However, a second hip strategy is used that utilizes a strong hip extensor moment to control for vertical collapse against gravity.[37] This hip strategy is thought to be used in large perturbations, or when the support base is smaller.[14] In this strategy, trunk and quadriceps muscles are activated in a proximal to distal sequence, rather than the primary activation of the lower leg musculature in a distal to proximal sequence as shown in the ankle strategy.[14]

In typically developing children, there is an increase in ankle strategy recruitment versus hip strategy recruitment as walking experience increases.[2,8] In children with cerebral palsy, the incidence of a hip strategy utilization increases as walking experience increases. A study by Burtner[2] has found that motor recruitment order reverses from an ankle strategy to a hip strategy even in normally developing children when they assume a crouch gait similar to that found in children with cerebral palsy. Therefore, the recruitment shift seen in cerebral palsy subjects may be attributed to crouch gait itself.[2]

In perturbation studies where a moving platform was displaced while a subject was standing bilaterally, the hamstrings preceded gastrocnemius activity by 25 and 31 milliseconds,[2,21] suggesting that spastic cerebral palsy patients utilize hip strategies when perturbed rather than the normal ankle strategies. This change in neural activation is thought to be the primary contributor to the co-contraction seen in many cerebral palsy subjects.[2,5] During a bilateral standing balance test, it was found that hamstring/gastrocnemius and quadriceps/tibialis anterior ratios for co-contraction were higher in the spastic limbs of cerebral palsy patients than the control group.[21] Likewise, it was found that extensor synergy (vastus medialis and gastrocnemius) was significantly different between children with CP and the control group.[40] This suggests further that co-contraction along with increased usage of extensors and hip strategies are used most in children with CP.

Co-Contraction as a Compensatory Mechanism

Subjects with pathologies such as anterior cruciate ligament (ACL) deficiencies, benign joint hypermobility syndrome, knee osteoarthritis, and general muscle weakness have been shown to have increased co-contraction in the lower extremity during postural and dynamic tasks.[7,11,15,31] Through these studies, it is suggested that there is a complex systematic sensory-

motor synergy existing between the ligaments, antagonist-agonist muscle pairs, mechanoreceptors, joint capsules and associated muscles around a joint. These complex synergies are exhibited mostly as muscle co-contractions and act as compensatory mechanisms for the pathologies' lack of joint stability.[7,15,31,32]

For example, in patients with a deficient ACL, it was demonstrated that antagonist muscles assumed the role of joint stabilizers during loaded knee extensions.[31] It is suggested that active muscle forces were necessary for the maintenance of equilibrium of the joint. In patients with benign joint hypermobility syndrome, a condition that results in increased range of motion of joints and lack of stability, there was a greater exhibition of co-contraction of the rectus femoris (RF) and semitendinosus (ST) during less challenging postural tasks such as bilateral quiet standing with eyes open.[11] Conversely, the non-hypermobile control group showed increased RF-ST co-contraction as a knee stabilization technique during challenging single leg standing tasks.[11] Since increased co-contraction is exhibited during a challenging postural task, it seems to be used as a compensatory stabilizing mechanism. Therefore, co-contraction would also be used in this manner by a patient with a pathological lack of stability.

In a study[7] looking at muscular co-contraction in a diverse group of active and non-active able-bodied women, it was suggested that during walking there was a significant negative correlation between flexor and extensor work and co-contraction in the non-active women. That is, increased co-contraction in the lower extremity decreased the amount of work that was able to be done during the walking task. It was indicated that women with a lower work-producing capacity have higher levels of co-contraction. Likewise, with the increase of muscle strength in the active women, there was a correlated decrease in requirement of muscle activation to achieve the same force output as non-active women. The author suggests that women compensate for muscular weakness by means of higher muscle activation levels. This most likely

occurs in attempt to generate adequate joint stiffness to counterbalance the effects of external loads.[7]

It is supported that co-contraction of the quadriceps and hamstrings increase compressive forces that improve contact between joint surfaces and increase knee stiffness to provide resistance to perturbations.[18] This suggests that strategies for stabilizing the body in pathologic conditions are correlated with muscle co-contraction. Furthermore, a pathological decrease in muscle co-contraction could predispose an individual to ligament injuries, absorption of potentially harmful loads and lack of intrinsic stabilization.[18] In conclusion, co-contraction is seen as a compensatory mechanism in most pathologies; whether it be for joint instability or general muscle weakness.

The analysis of the literature leads one to propose that this higher level of co-contraction seen in cerebral palsy could be helpful in decreasing fall risk by stabilizing the ankle, knee and hip joints as a compensation mechanism for the points mentioned above. However, if the increased level of co-contraction was a one-directional increase, meaning, only at the hip, knee, or ankle, this could decrease musculature available to successfully return to a balanced position.

Center of Pressure Excursion

In relation to balance, COPE is defined as the displacement of the summed center of force of a subject and can be measured in the anteroposterior and mediolateral directions.[16] COPE is a popular measurement when quantifying postural sway, as using this measure can quantify sway amplitudes, sway path, and sway area. Ideally, the body should be able to recover from perturbations using quick COP transitions that generate forces in the opposite direction of a fall to accelerate the body and maintain balance. However, it has been shown that subjects

with decreased sensory-motor system performance caused by anomalies such as musculoskeletal disorders, aging, and neurological conditions have a deterioration of the proprioceptive mechanisms that assist in balance abilities as measured by COP mean displacements, velocity, sway path, sway amplitude, and sway frequency.[16,23,26,28] Further, in a study by Hufschmidt[16] the COPE mean amplitude is equated to postural instability, while the sway path indicates balancing ability. Larger sway paths and increased sway amplitude have been correlated to neurological abnormalities such as cerebellar and vestibular postural ataxias caused by anterior lobe atrophy, cortical cerebellar atrophy or Labyrinthine Lesions.[16] Likewise, it was found that mean sway frequency, mean total power in the anteroposterior direction and mean COPE velocity increase with age, which indicates increased effort to maintain postural stability when compared with a younger population without decreased sensory-motor system performances. From this, COPE velocity has been shown to detect changes in postural sway due to aging.[19]

Consistent with these findings, Callahan[3] found that there were significant differences in mean COPE velocity between subjects with cerebral palsy who were classified as high and low fall risk cohorts. Subjects with a higher fall risk had a higher COPE velocity. Since COPE has been shown to be able to assess changes in balance abilities of other neurological disorders, it would be feasible that fall risk could be inferred from COPE measurements in cerebral palsy patients with sensorimotor abnormalities.

CHAPTER THREE: METHODOLOGY

The methodology section describes the steps taken to determine the relationship between COPE measures, CP fall risk, and muscle synergy. It contains information regarding research design, subject demographics, instrumentation, data collection, data processing and data analysis procedures.

Participants

All collection procedures and processing followed the outline by Callahan[3] to analyze COPE during a SLST. For this study, 27(12F, 15M) self-ambulating children with spastic cerebral palsy (CP) (age 13.9 ± 3.8, mean ± SD) were recruited and analyzed using kinematic and EMG data (Table 1).

Table 1. *Subject demographics including age, gender, device used (c = crutch, w = walker), GMFCS (gross motor function classification score), diagnosis (D = diplegic, H = hemiplegic), and fall risk as defined by reported fall frequency.*

Subject	Age	Gender	Device?	GMFCS Score	Diagnosis	Fall Risk
1	15.5	M	No	2	D	Low
2	17.4	F	No	2	D	High
3	12.9	M	No	2	D	High
4	13.8	M	No	1	D	High
5	10.3	M	No	1	D	High
6	8.3	M	No	1	D	High
7	19.7	F	No	2	D	High
8	17.7	F	No	1	D	Low
9	8.2	M	No	1	D	High
10	16.2	F	Yes, c	3	D	High
11	18.0	M	No	1	D	Low
12	10.0	M	No	2	D	High
13	13.2	M	No	1	H	Low
14	17.8	F	Yes, w	3	D	Low
15	8.6	F	No	2	D	High
16	12.3	M	No	2	H	High
17	16.6	M	No	1	H	Low
18	12.2	F	No	1	D	Low
19	12.0	F	No	1	D	Low
20	15.8	M	Yes, c	3	D	Low
21	15.1	M	Yes, w	3	D	Low
22	6.0	F	No	1	D	Low
23	18.8	M	No	1	D	Low
24	17.1	M	Yes, c	3	D	Low
25	12.1	F	No	2	D	Low
26	11.4	F	Yes, w	3	D	Low
27	19.1	F	Yes, w	3	D	Low
Average	13.9					
SD	3.81					

After thorough explanation of study protocol and discussion of any questions, verbal and written assent and consent were obtained from all participants prior to performing any analysis during the clinic visit. Participants between 12-17 years old signed the assent form along with their legal

guardian, and subjects under 11 years old required their legal guardian's signature only. Exclusion criteria included inability to follow directions due to intellectual disabilities, inability to self-ambulate, and previous (within 6 months) surgical procedures. Subjects who used assistive devices such as crutches or walkers were included. A fall risk questionnaire was administered to assess fall risk. This questionnaire included questions regarding CP diagnosis, age, gender, dominant limb, self-reported fall frequency within 30 days, and hospital visits due to recent falls.[3] Participants were then marked using a modified Cleveland Clinic marker set to obtain kinematic data. Concurrently, wireless surface EMG electrodes were placed on 7 muscles of interest. The kinematic data were used to identify time periods in which the subject was in quiet bilateral stance, single leg stance, and when the subject regained bilateral stance. These time periods were used to specify the EMG data that should be regarded as "quiet stance" versus an active single leg stance trial. Subject data were then separated into fall risk cohorts using fall risk as defined by the COPE velocity and fall risk relationship found by Callahan[3] and statistically analyzed.

Procedures

Collection of EMG and Kinematic Data

3-Dimensional kinematic data were collected at 240Hz using a Motion Analysis system with 12 Eagle digital cameras and Cortex (Version 5.50179) software (Motion Analysis Corporation, Santa Rosa California). Surface EMG data were recorded at 960Hz using a Delsys Trigno Wireless EMG system (Delsys Inc., Natick, MA). Following shaving (when required) and debridement and cleaning of the skin, bipolar wireless electrodes (Ag/Ag) were placed on the following 7 muscles: adductor magnus (HAD), gluteus maximus (GMX), gluteus medius (GMD), medial hamstrings (MHM), rectus femoris (REC), tibialis anterior (TIB), and gastrocsoleus(GAS). All EMG electrodes were placed while the subject was sitting except for the gluteal muscles,

when the subject was standing. EMG electrodes were placed perpendicular to muscle fiber direction according to SENIAM[13] and Shriners Medical Center protocol as expressed in Table 2.

Table 2. *Description of electrode placement for eight muscles (Anterior Tibialis, Gastrocsoleus, Medial Hamstrings, Adductors Magnus, Rectus Femoris, Gluteus Medius, and Gluteus Maximus).*

Muscle	EMG Placement
Anterior Tibialis (TIB)	Placed on the most proximal, medial portion of the muscle belly, just distal to the tibial tuberosity and lateral to the tibial crest
Gastrocsoleus (GAS)	First electrode placed on the most proximal posterior mass on the medial head of the gastrocnemius. Second electrode placed distal to the first over the soleus fibers.
Medial Hamstrings (MHM)	Placed over the distal 1/3 of the semitendinosus muscle belly on the posterior thigh midway between the medial epicondyle of the femur and ischial tuberosity.
Adductors Magnus (HAD)	Placed on the medial thigh, midway between the medial femoral epicondyle and the pubic tubercle.
Rectus Femoris (REC)	Placed on the anterior thigh, midway between the superior border of the patella and the anterior superior iliac spine (ASIS).
Gluteus Medius (GMD)	Placed on the midpoint of the iliac crest at the halfway point between the crest and the greater trochanter.
Gluteus Maximus (GMX)	Placed on the most proximal posterior portion of the muscle just below the posterior superior iliac spine (PSIS).

For subjects 1-16, the EMG channels were converted with 12-bit resolution at a rate of 960 samples per second. For subjects 17-27, the EMG channels were converted with 16-bit resolution at a rate of 960 samples per second.

Single Leg Standing Test

EMG and kinematic data were collected during a SLST performed on an AMTI OR6-5 force platform (AMTI Corporation, Watertown, WA). During the SLST, subjects were asked to position themselves on the force platform, then to shift to stand on one leg. To familiarize themselves with the procedure, subjects stood on the right foot with the left foot off the ground for 3 trials for a self-selected time-period, then switched to have the left foot on the ground with the right foot off the ground for 3 trials. After familiarization, participants attempted three 10-second SLST trials with each leg, starting with 3 trials with the right leg off the ground and

finishing with 3 trials with the left leg off the ground. The subjects that were unable to perform a 10-second trial were informed to stand on one leg for as long as possible. End of the trial was regarded as the regeneration of bipedal stance.

Data Processing

Marker trajectory data were collected and tracked using Cortex (Version 5.50179) software and processed using Visual 3-D (Version 5.0123) software (C-Motion Inc., Germantown MD). Kinematic time points were identified to mark events during the trial and were labeled as left or right stance initiation (LSI, RSI), foot off (LFO, RFO), foot down (LFD, RFD), and stance termination (LST, RST). These marked events served as reference points to determine quiet standing and single leg stance (SLS) for EMG and data processing.

EMG data were processed in MatLab (Version R2017b). Due to the spastic muscle activity common in children with CP, it was necessary to determine true active muscle activity during the standing test rather than EMG noise from muscular spasticity. Therefore, rectified and unfiltered EMG data were used for each muscle during quiet standing to obtain a baseline of "quiet," or "off," EMG amplitude. Quiet standing was defined as the period of time before the LSI or RSI. Data found during this period were averaged and 2 standard deviations were added to the average value to indicate that the muscle was meaningfully active. This was referred to as the "cutoff" amplitude.[36]

Once the cutoffs for each muscle were calculated, data were full wave rectified and low pass filtered at 6Hz using a 2nd order Butterworth filter. True muscle activity during the SLST was defined as all EMG values above the specified cutoff value for the specified muscle. The muscle activity for each subject was normalized to the peak activation level during the SLS task. This method of normalization has been found to decrease data variability between individuals and

be a reliable method of activation pattern normalization between individuals over time compared with normalization using maximal voluntary isometric contractions (MVIC).[12,30]

Synergistic Groups

Synergistic groups were developed by identifying hip, knee, and ankle musculature. Hip musculature was identified as the HAD, GMX and GMD; knee musculature the MHM and REC; and ankle musculature the TIB and GAS. The grouping of these muscles is expressed in Table 3.

Table 3. *Muscle synergy group compositions.*

Sagittal Hip	Knee	Ankle	Frontal Hip
GMD	MHM	TIB	GMD
GMX	REC	GAS	HAD

Gmd: gluteus medialis; Gmx: gluteus maximus; Mhm: medial hamstring; Rec: rectus femoris; Tib: tibialis anterior; Gas: gastrocsoleus; Had: adductor magnus

Sagittal and frontal planes of motion were also considered in the grouping of muscles. Sagittal Hip synergy was meant to view co-contraction index values in relation to muscles acting along the sagittal axis, whereas the Frontal Hip, Knee and Ankle synergies view values in relation to muscle movement along the frontal axis. This was to identify a potential difference in balance control originating from frontal or sagittal motor groups.

To calculate a co-contraction index for each synergistic group, the linear envelopes of each muscle included in the synergy group were plotted together and the area of the overlap of the envelopes were calculated. The calculated area was divided by the number of data points to determine the co-contraction index for that particular synergistic group. Once co-contraction indices were calculated for left and right legs, the groups were averaged together to serve as the final co-contraction indices under analysis.

Fall Risk Grouping

Fall risk groups were formed using the concept expressed by Callahan[3] that higher fall risk is correlated with lower COPE velocities. First, participants were grouped into high fall risk and low fall risk groups based on the fall risk cohort inclusion criteria outlined by Callahan.[3]

Participants with reported falls greater than 5 falls in a month's time were segregated into the high fall risk group, and participants with reported falls less than 5 falls per month were placed into the low fall risk group. Then, the average COPE velocities were calculated for the high and low fall risk groups (as defined above) and used as guidelines to place the subjects into high and low fall risk cohorts based on COPE velocity. This grouping method was referred as "fall risk based on COPE velocity."

Statistical Analyses

Independent t-tests were performed to test the first hypothesis that high fall risk and low fall risk CP subjects have different values of coactivation within recruited muscle synergies when performing a single leg standing test when the fall risk is defined by COPE velocity. Variables tested included co-contraction indices for Sagittal Hip, Knee, Ankle, and Frontal Hip synergistic groups differentiated by fall risk as defined by COPE velocity. Differences between the means of the synergies will indicate difference in muscle recruitment between low and high fall risk individuals.

The second hypothesis was tested by performing two nonparametric analysis of variance (ANOVA) tests on the low and high fall risk groups separately to determine if specific muscle synergies have greater incidences of activation depending on fall risk. Initial significance of the ANOVA tests indicated that there is a significant difference between at least two of the synergy groups. Therefore, a post-hoc nonparametric t-test, the Tukey method, was used to identify which groups were different. Differences in the means between synergy groups within the two separate fall risk groups would indicate muscle synergy activation differences within the high and low fall risk groups.

A Pearson correlation test was performed to test the third hypothesis that there is a relationship between COPE velocity and synergistic muscle group co-contraction indices. Variables included in the correlation matrix were the mean co-contraction indices for Sagittal Hip, Knee, Ankle and Frontal Hip synergistic groups and COPE velocity for all subjects. A correlation between co-contraction index and COPE velocity could indicate a general relationship between COPE velocity and muscle activation. Correlation coefficients were interpreted as very strong ($r = 0.80 – 1.0$), strong ($r = 0.60 – 0.79$), moderate ($r = 0.40 – 0.59$), weak ($r = 0.20 – 0.39$) and negligible ($r = 0.00 – 0.19$)[9].

All statistical analyses were performed using SPSS 24 (SPSS Inc., Chicago, IL). A significance level of $p < 0.05$ was used for all statistical tests.

CHAPTER FOUR: RESULTS AND DISCUSSION

The results section presents the statistical findings regarding the relationship between COPE measures, CP fall risk and muscle synergy. This includes independent t-test analyses, two nonparametric analysis of variance (ANOVA) (Kruskal-Wallis H tests) with post-hoc tests using the Tukey method, and correlation analysis conducted on the data collected.

Subject Demographics

Data analysis and processing were performed on 27 subjects; 12 females and 15 males, with a mean age of 13.9 ± 3.8 years old. Out of the 27 subjects, 7 required the use of their normal assistive ambulatory devices; 3 of which used crutches and 4 used walkers. The rest of the 20 subjects were independently ambulatory. There were 3 subjects who were diagnosed with spastic hemiplegic cerebral palsy, while 24 were diagnosed with spastic diplegic cerebral palsy. The division of fall risk groups into +/- 5 reported falls resulted in 15 subjects (5 falls or less) in a low reported fall risk group, and 12 subjects (greater than 5 falls) in the high reported fall risk group.

COPE velocity average and standard deviation were calculated to be 0.2777 ± 0.1418 m/s for subjects with a fall frequency reported above 5 falls in a month's time (high reported fall risk). COPE velocity average and standard deviation were calculated to be 0.1834 ± 0.1198 m/s for subjects with a fall frequency reported below 5 falls in a month's time (low reported fall risk). The two averages were themselves averaged together to equal 0.2305 m/s, and this value was used as the cutoff velocity for COPE velocity dependent high and low fall risk groupings. Subjects with a COPE velocity greater than 0.2305 m/s were placed in the high fall risk group, and subjects with a COPE velocity less than 0.2305 m/s were placed in the low fall risk group. 16 participants were grouped into the low fall risk cohort and 11 participants into the high fall risk

cohort. All statistical analyses were performed on the high and low fall risk groups that were determined by COPE velocity.

Fall Risk and Muscle Synergy

Independent t-tests were performed between Sagittal Hip, Knee, Ankle, and Frontal Hip synergistic groups across the fall risk groups. No significant differences (p = 0.476, 0.076, 0.064, 0.364) were found in co-contraction index values between high and low fall risk groups. The mean ± standard deviation of these synergy groups and the relationships between groups are expressed in Table 4.

Table 4. *T-test results for synergy group differences between high and low fall risk groups.*

Synergy Group	Sagittal Hip		Knee		Ankle		Frontal Hip	
	High Risk	*Low Risk*	*High Risk*	*Low Risk*	*High Risk*	*Low Risk*	*High Risk*	*Low Risk*
Mean	49.86	43.20	34.58	46.83	16.28	26.42	17.52	20.58
Standard Deviation	27.23	27.71	19.66	23.16	15.09	18.27	22.16	22.35
Significance	0.476		0.076		0.064		0.364	

Two nonparametric repeated measures ANOVA tests were performed on the synergy groups within the fall risk groups themselves. The high fall risk cohort was found to be significant for an F value of 4.676 (p = 0.007), indicating that there is a significant difference between at least two co-activation groups. A Tukey's post-hoc test found that there are significant differences between the sagittal hip and ankle groups (p = 0.016) and the sagittal and frontal hip groups (p = 0.022). No other significances were found between synergistic groups. Mean differences, standard errors and significance values of the synergistic groups are consolidated in Table 5.

Table 5. *Tukey's Post Hoc test results for Muscle Synergy group co-contraction index values within the High Fall Risk classification.*

(I)Synergy Group	(J) Synergy Group	Mean Difference (I-J)	Std Error	Significance
Sagittal Hip	Knee	10.77	9.171	0.646
	Ankle	29.07*	9.171	0.016
	Frontal Hip	27.81*	9.171	0.022
Knee	Ankle	18.29	9.368	0.224
	Frontal Hip	17.03	9.368	0.281
Ankle	Fontal Hip	-1.260	9.368	0.999

*Denotes significant differences in the Co-Contraction Index for sagittal hip and ankle groups and sagittal hip and frontal hip groups at $p < 0.05$.

Table 6. *Tukey's Post Hoc test results for Muscle Synergy group co-contraction index values within the Low Fall Risk classification.*

(I)Synergy Group	(J) Synergy Group	Mean Difference (I-J)	Std Error	Significance
Sagittal Hip	Knee	-3.636	8.199	0.971
	Ankle	16.78	8.199	0.184
	Frontal Hip	22.62*	8.199	0.038
Knee	Ankle	20.42	8.199	0.073
	Frontal Hip	26.25*	8.199	0.012
Ankle	Fontal Hip	5.837	8.199	0.892

*Denotes significant differences in the Co-Contraction Index for sagittal hip and frontal hip groups and frontal hip and knee groups at $p < 0.05$.

The low risk cohort was found to have significance in at least two of the groups, with an F value equal to 4.826 and p=0.0047. A Tukey's post-hoc test found significant different co-activation values between the means of the sagittal and frontal hip groups ($p = 0.038$) and knee and frontal hip groups ($p = 0.012$). Mean differences, standard errors and significance values of the synergistic groups are consolidated in Table 6.

COPE Velocity and Co-contraction Index

A Pearson correlation test was performed between COPE velocity and synergistic muscle group co-contraction indices. Weak and insignificant negative correlations were found between COPE velocity and the knee and ankle groups (r = -0.309, -0.323, p = 0.059, 0.050). Negligible and insignificant correlations were found between frontal hip and sagittal hip synergies and COPE velocity (r = 0.013, -0.068, p = 0.475, 0.367). Pearson correlation r values and their significances are found in Table 7.

Table 7. *Results of a Pearson correlation between COPE velocity and Muscle Synergy Co-Contraction indices.*

		Sagittal Hip	Knee	Ankle	Fontal Hip
COPE Velocity	Pearson Correlation	0.013	-0.309	-0.323	-0.068
	Sig. (1-tailed)	0.475	0.059	0.050	0.367
	N	27	27	27	27

Discussion

As reported, mean co-contraction indices did not significantly differ from one another when high and low fall risk groups were compared.

However, the mean co-contraction indices of the sagittal hip and knee groups were significantly greater than the other synergy groups within the high and low fall risk groups separately. These findings are consistent with studies that state that rectus femoris and hamstring co-contraction indices are increased in muscularly weak subjects, persons with hypermobile joints and those with deficient ACL stability.[7,8,11,31,36] Likewise, they are consistent with previous studies that found that CP populations tend to reverse the typically recruited distal to proximal balance strategy.[2] The findings suggest that a knee and hip strategy are recruited more than an ankle strategy in a balance task, specifically a single leg standing task, regardless of fall risk.

Finally, it was found that there are weak and negligible relationships between co-contraction indices in synergy groups and COPE velocity. Significant correlations between co-contraction index value and COPE velocity would have indicated that as fall risk grouping decreases from high-risk to low-risk, the co-contraction index between the rectus femoris and medial hamstrings, and gastrocsoleus and tibialis anterior increases. This is consistent with the literature that states that co-contraction functions as a joint stabilizing mechanism.[6,7,8,11,31,36] With increased joint stabilization via co-contraction, increased stability is achieved.

CHAPTER FIVE: SUMMARY, RECOMMENDATIONS, CLINICAL IMPLICATIONS, AND CONCLUSION

This section will address and summarize the specific conclusion of the relationship between COPE measures, CP fall risk and muscle synergy. This section will also identify recommendations for future research and clinical implications regarding muscle synergy and the cerebral palsy population.

Summary

The goal of this study was to explore the relationship between COPE measures, fall risk and muscle synergy activation during a SLST. This was to expand understanding of muscle synergies and their recruitment in the CP population. This knowledge could potentially uncover the specific causes of balance impediment and increased fall risk as found in this subject group.

The results of the t-test performed between synergy groups in high and low fall risk groups were inconsistent with the first hypothesis, as the mean co-contraction index values did not significantly differ from one another when high and low fall risk groups were compared.

The results of nonparametric ANOVA and post-hoc tests performed within the fall risk groups were consistent with the second hypothesis. In the high fall risk group, the mean co-contraction indices of the sagittal hip group were significantly greater than the frontal hip group indices. The sagittal hip group indices were also significantly greater than the ankle group indices. Within the low fall risk group, the sagittal hip group indices were significantly greater than the frontal hip group co-contraction indices, and the frontal hip group indices were significantly smaller than the knee group.

Finally, it was found that there are weak and negligible relationships between co-contraction indices from all analyzed synergy groups and COPE velocity.

Delineations and Recommendations for Future Research

There are several delineations for this study. Firstly, although all the children included in the trials were self-ambulatory, there were 7 subjects allowed to use their normal assistive devices, which included walkers and crutches. This could have influenced the ability to stand for longer periods of time or required different group recruitment as compared with free standing subjects. For a future study, it would be ideal if device usage was considered an exclusion criterion.

Secondly, there were 3 children included in the study who were diagnosed with hemiplegic cerebral palsy, and 24 who were diagnosed with diplegic cerebral palsy. It would be beneficial for a future study to recruit equal participants from each category to see if there are differences in co-contraction amount in diplegic and hemiplegic diagnoses.

Lastly, the more affected leg in the subjects was not considered in the calculation of the co-contraction indices. Future studies could investigate the differences in co-contraction and muscle activation in affected versus unaffected (or less affected legs) in relation to fall risk to further investigate muscle synergy behavior in the CP population.

Clinical Implications

A common method to reduce contracture is the posterior tibialis tendon or Achilles tendon transfer, which consists of the release, rerouting, lengthening and transfer of the tendons to reduce contracture in the gastrocsoleus area. The posterior tibialis is thought to be the source of deforming forces,[33] but the ability to identify specifically recruited musculature during a functional task could help shed light on other surgical procedures that could be more viable and reliable options for treating contractures.

Using EMG to analyze motor recruitment along with gait analysis could benefit physicians by allowing a critical assessment of the specific pathologies of unique patients. It

could also be an accurate and quantifiable assessment of post-treatment outcome.[10] Likewise, using EMG as an assessment tool for motor group recruitment could help separate abnormalities from secondary coping mechanisms. Being able to quickly and correctly identify the chief anomaly during a patient assessment could save the patient and physician time and money.

The loose identification of the gluteus maximus, gluteus medius, medial hamstring, and rectus femoris as a factor of fall risk in terms of COPE velocity increases the importance to focus on these two-joint muscles with strengthening methods and therapy to reduce fall risk in populations whose balance is hindered. Utilizing a more objective assessment like EMG during a simple balance task can help identify factors that lead to increased fall risk and uncover the specific pathology of a patient's postural imbalance. These discoveries can then lead to a more personalized and unique method of therapy and treatment for the diverse cohort that is the cerebral palsy population.

Conclusion

With the findings presented, there is insufficient evidence to claim that specific muscle group activations are different depending on fall risk determined by COPE velocity. Furthermore, the insignificance of the correlations found in the current study suggest that it is not currently possible to correlate COPE velocity to a specific synergy group recruitment. These results are most likely due to the highly variable and unique contracture qualities among CP patients.

However, the significant differences in the data within each group suggest that sagittal hip and knee strategies are recruited more than ankle and frontal hip strategies during a balance task, specifically a single leg standing task, regardless of fall risk in the cerebral palsy population.

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