JUMP PERFORMANCE AND ITS RELATIONSHIP WITH LOWER BODY JOINT KINETICS AND KINEMATICS IN CHILDREN WITH CEREBRAL PALSY

by

SHELBY ELIZABETH THOMPSON, B.S.

(Under the Direction of Christopher Modlesky)

ABSTRACT

PURPOSE: The aim was to determine if there is a deficit in jump performance in children with cerebral palsy (CP) and if the expected deficit is related to discrepancies in their lower body joint kinetics and kinematics.

METHODS: Seventeen children with CP and 17 matched controls were studied. Jump height and lower body joint kinetics and kinematics were assessed during a countermovement jump.

RESULTS: Compared to controls, children with CP exhibited lower jump height, knee and ankle joint power, maximal knee flexion and extension, and maximal ankle dorsiflexion and plantarflexion (all $p < 0.05$). The lower jump height in children with CP was associated with lower knee and ankle joint power, maximal knee flexion and extension, and maximal ankle dorsiflexion and plantarflexion (all $p < 0.05$).

CONCLUSION: Children with CP have a lower jump height which is associated with lower joint power generation and range of motion in the lower body.

INDEX WORDS: Cerebral palsy, Physical activity, Vertical jump, Joint power, Joint angles

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SHELBY ELIZABETH THOMPSON

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JUMP PERFORMANCE AND ITS RELATIONSHIP WITH BIOMECHANICAL MARKERS IN CHILDREN WITH CEREBRAL PALSY

by

SHELBY ELIZABETH THOMPSON

Major Professor: Christopher Modlesky

Committee: Harshvardhan Singh
Tarkeshwar Singh
Li Li

Electronic Version Approved:

Ron Walcott
Vice Provost for Graduate Education and Dean of the Graduate School
The University of Georgia
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DEDICATION

This paper is dedicated to the children who have participated in this study, and to all children with cerebral palsy. You are limitless, invincible, and awe inspiring

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CHAPTER 1

INTRODUCTION

Cerebral palsy (CP) is a permanent movement disorder that affects approximately 3.2 per 1000 children in the United States [1, 2]. Children with CP have profound motor deficiencies, resulting in significant muscle weakness and a limited muscle power generation [3]. These motor control impairments, combined with poor muscular function, contribute to a lack of physical fitness [4] and participation in physical activity [5]. Along these lines, jumping has been noted to be an important skill in many physical activities as it promotes muscle [6] and bone growth [7-9]. Plyometric jump training helps children improve their coordination, balance, posture, flexibility [10], and metabolic rate [11]. Unfortunately, many children with CP may be unable to participate in plyometric activities due to impairments that limit their jumping ability. Because jump performance has been linked to physical activity participation [12], it is critical to investigate the biomechanical components that contribute to jump performance in children with CP. Furthermore, the physiological differences in performance markers identified while jumping could be indicators of injury risk [13-15]. Despite the noted benefits of jumping, the positive correlations between jump performance and physical activity, and biomechanical differences during jumping, there is a lack of literature investigating these factors in children with CP.

Statement of the Problem

Neuromuscular control, strength, and coordination are negatively impacted in children with CP and result in low participation in physical activity. Vertical jumping is a key skill necessary to participate in many physical activities, but most children with CP are unable to jump or have limited jumping ability. Unfortunately, few studies have assessed vertical jump performance in adults with CP, and none have assessed jump performance in children with CP. Assessing jump performance could be helpful to researchers and clinicians because it may give a deeper understanding into the biomechanical deficits in children with CP and assist in the development of effective treatment strategies.

Specific Aims

Aim 1: To determine if there is a deficit in jump performance in children with CP.

Aim 2: To determine if the expected deficit in jump performance in children with CP is related to discrepancies in their lower body joint kinetics and kinematics.

Hypotheses

Hypothesis 1A: Jump performance, as reflected by jump height in the preparatory phase, will be lower in children with CP than in typically developing children.

Hypothesis 1B: During the preparatory phase, power generation will be lower at the hip, knee, and ankle in children with CP compared to typically developing children

Hypothesis 1C: During the preparatory phase, sagittal angles will be lower at the hip, knee, and ankle in children with CP compared to typically developing children

Hypothesis 2A: There will be a significant relationship between jump height and hip, knee, and ankle joint power during the preparatory phase of the vertical jump.

Hypothesis 2B: There will be a significant relationship between jump height and the expected sagittal angle deficits of the hip, knee, and ankle in the preparatory phase of the vertical jump.

Significance of the Study

The proposed study is significant because children with CP participate in less physical activity than typically developing children. Although it has been demonstrated that children with CP benefit from plyometric jump training, jump performance has not been studied. Specifically, the impact of physiological manifestations of CP on jump performance has also not been investigated. This is important because jumping is a common component of vigorous physical activity. Through a comprehensive assessment of kinetic and kinematic variables, we will determine if physiological abnormalities present in children with CP will impact vertical jump performance. The findings of this study will aid in the development of preventative therapies to avoid future injuries and encourage children with CP to engage in vigorous physical activity.

CHAPTER 2

LITERATURE REVIEW

2. 1 Cerebral Palsy

Cerebral palsy is the most common cause of motor deficiency in young children and occurs in approximately 3.2 per 1000 live births [1, 16-18]. Cerebral palsy represents an array of disorders of movement and posture which cause limitations in activity. These disorders are attributed to nonprogressive disturbances that occurred in the fetal or infant brain [2, 19, 20]. They are characterized by a heterogeneous group of neuromotor conditions including disruptions in sensation, perception, cognition, communication, and behavior disorders [2, 20], as well as muscle weakness, musculoskeletal disorders, and articular instability [21]. Individuals with CP have a persistent deficit in their locomotion pattern and orthostatic position. Cerebral palsy and associated motor delays including learning to roll over, sit, crawl, and walk are frequently diagnosed within the first few years of life.

Cerebral palsy can be classified by topography. This includes monoplegia, diplegia, hemiplegia, and quadriplegia. Monoplegia is the least common type of CP affecting one limb. Diplegia impacts both sides of the body and impacts the lower limbs more than the upper limbs. Hemiplegia is prominent on one side of the body and typically impacts the upper limbs more than the lower limbs, causing reduced synchronization and weight-bearing differences due to more and less affected limbs [22]. Quadriplegia impacts both sides of the body with upper and lower limbs equally impaired. Quadriplegia tends to impact the mouth, face, and trunk [19].

Cerebral palsy is also classified into motor types: spastic, dyskinetic, hypotonic, and ataxic [23], with spastic as the most prevalent [1, 17, 18]. Damage to the motor cortex causes spasticity and is characterized as a velocity-dependent, increased resistance to stretch due to increased muscle tone [19, 23]. This causes stiffness and rigidity with movement. Spastic catches can be felt with certain movements in children with CP, primarily with movement in the lower limbs causing flexed posture [24].

Some symptoms of CP, such as loss of postural control and difficulty with movement, might lead to the development of musculoskeletal problems [25]. Spasticity is a motor deficiency characterized by velocity-dependent resistance in which muscles are unable to relax, causing stiff movements [26]. Muscle relaxation and contraction are necessary to perform movement, which can be impacted by involuntary muscle contractions known as spasms. Spasms can add strain on joints, particularly the hip, knee, and ankle [27]. Spasticity in the musculature surrounding the knee, such as the hamstrings, quadriceps, and gastrocnemius, is the most common cause of knee pain in people with CP, particularly in the patellofemoral joint after walking with increased knee flexion [28]. Spasticity can also be present with spasms and add strain on the knees and limit range of motion. Additionally, given that spasticity at the ankles is greater than the knees in children with spastic diplegic CP [29], limited ankle joint movement is prevalent [30] and is linked to deficiencies in gait and balance performance in children with CP [31, 32].

Muscle imbalance can cause gait abnormalities or dysfunction when muscles are stronger one side and too weak on the other due to spasticity [33, 34]. Crouch gait is one of the most common gait patterns associated with CP, and is very common in children with CP [35] with wide ranging prevalence rates of 15% [36] to 74% [37]. Crouch gait, a severe sagittal plane deviation, is characterized as excessive ankle dorsiflexion of less than 50 degrees, as well as knee and hip flexion of 8 to 30 degrees [29, 38-40]. Previous studies utilized knee position angles during different parts of the gait cycle to identify other gait patterns [35]. Some of these gait abnormalities include true equinus and jump knee apparent equinus [41]. The strength of the lower limb muscles of children with spastic CP is less than that of typically developing children [42, 43] indicating that their muscle weakness may potentially cause increased knee flexion and ankle dorsiflexion during walking [33, 44]. Prior studies have investigated how crouched postures affect the ability of muscles to extend the hip and knee joints, as well as the joint flexions caused by gravity during the single-limb stance phase of gait. The findings indicate that in a crouched posture, nearly all of the major hip and knee extensors' capacities are significantly reduced, with the exception of the hamstrings muscle group, which maintains its extension ability. During single-limb stance, crouch gait enhances the flexion accelerations caused by gravity at the hip and knee [33].

In addition to its negative impact on an individual's ability to move, CP is associated with several co-existing neurological impairments that have an impact on activities and participation in society, such as learning problems, epilepsy, vision impairment, and hydrocephalus, as well as speech, language, perceptual and behavioral deficiencies. [45]. The frequency and severity of related deficits increases with the severity of motor impairment in many children with CP [19]. For example, high myopia, lack of binocular fusion, dyskinetic strabismus, severe gaze dysfunction, and optic neuropathy or cerebral visual impairment were the most common symptoms in children with level 5 classification (the most severe). In children with the mildest deficits indicated in level 1 classification, these visual impairments were rare or nonexistent [46]. According to prior research, related impairments have a greater impact on function and quality of life than the motor impairment alone. Epilepsy, for example, affects 30 to 50 percent of children with CP, especially those who have restricted mobility [47]. Independent of antiepileptic drug use or seizure management, people with epilepsy exhibit considerable changes in balance and movement. These changes are reflected in a lack of self-reported confidence in doing daily tasks [48]. The presence of these secondary conditions may make therapy treatments more difficult, lowering overall health and quality of life for the individual and their family [49], as well as increasing situational costs which could have a significant impact based on socioeconomic status [16].

The most widely used and well-validated measure of grow motor function in individuals with CP is the Gross Motor Function Classification System (GMFCS) [50]. The GMFCS is a five-level classification system for people with CP based on gross motor function. The person's ability to self-initiate movement, with a focus on sitting, transferring, and mobilizing, is used to classify each level [50]. At different ages, several classification descriptions exist. Approximately 40% of children change classification levels by the age of two [51] at which time GMFCS stabilizes and classification is more reliable [52]. In general, those classified as level I and II are considered ambulatory and are able to walk without the assistive devices. Level II may have slightly impaired balance. Those classified as level III may be able to walk short distances without assistance, but typically need assistive devices including wheelchairs for longer distances. Individuals in level IV and V are not ambulatory without an assistive device. Those classified as level V are limited to a manual wheelchair with limited ability to control posture and little to no independent movement [52].

2.2 Physical Activity

2.2.1 Methods to assess physical activity

Physical activity is defined as any body movement produced by skeletal muscles that results in energy expenditure [53]. It can be classified as occupational, sports, conditioning, household, or other activity. The amount of energy expended is expressed as a rate (kcal per unit time) or by a metabolic equivalent (MET). One MET is the amount of oxygen consumed while sitting at rest. Various methods for determining an individual's energy expenditure per unit time and estimating physical activity are currently available. These methods often include: 1) calculating the amount of calories consumed per unit time in order to maintain body weight; 2) questionnaires on daily activities; 3) a journal or activity log; 4) continuous indirect calorimetry with various types of respirometers; 5) the use of individual oxygen consumption with heart rate regression, followed by continuous heart rate monitoring [54]. More recently, activity monitors, which are often accelerometer-based, have been used to provide objective estimates of physical activity. The main function of activity monitors is to translate motions into electrical signals (counts) that are proportionate to the muscle force creating motion [55]. These counts are totaled and stored for a specific period of time (epoch). Activity monitor counts can be matched to a laboratory-established cut points to determine MET values. Many activity monitors have enough memory to track activity for up to 21 days using a 60-second epoch. Accelerometers have been used in a number of study contexts and have been reported as a reliable and valid measure of physical activity in a wide range of populations, from children to the elderly [55].

According to a study conducted by Troiano et al. in 2008, the quantity of physical activity as detected by an accelerometer can be displayed in three different ways: 1) mean counts per minute, 2) time spent in physical activity based on count thresholds, and 3) adherence to physical activity recommendations. The raw data provided by the ActiGraph GT9X Link, a commonly used accelerometer, is evaluated using mean counts per minute without any external criterion other than the evaluation of wear and non-wear time. The sum of activity counts for a valid day is divided by the number of minutes of wear time in that day across all valid days to get the mean counts per minute [56].

While accelerometer-based activity monitors provide valuable objective information, there are also several limitations to note. When worn over the hip (a common placement position), accelerometer-based activity monitors primarily monitor locomotor activity and hence overlook upper body movement. Furthermore, accelerometer-based activity monitors are unable to determine whether or not a person is carrying any weight (e.g., walking carrying something heavy expends more energy vs walking without a load). Similarly, as accelerometer-based activity do not track body posture, they cannot distinguish the difference between sitting and standing motionless [57].

Commercial accelerometers currently use piezoresistive and capacitive technologies to induce resistive changes in the strain gages that are a part of the seismic system of accelerometers. The ActiGraph monitors, which rely on activity-count-based algorithms [56] or self-report records to establish monitor wear-time, are widely used. ActiGraph's GT9X Link uses a capacitive proximity sensor that detects skin contact to distinguish between wear and non-wear to improve wear-time sensing [58]. These monitors have been identified as valid tools for measuring raw activity volume among children with CP and are suitable for use in research seeking to define this population's physical activity [59].

2.2.2 Classification of physical activity

Physical activity is performed at varying intensities, ranging between light, moderate, and vigorous intensity [60]. The amount of time spent in these activities is calculated by adding minutes each day where the count (amplitude and frequency of acceleration over a sample interval) met the criteria for that intensity [56]. Light intensity activities require the least amount of effort and are classified as less than 3 METS. Some examples of light intensity activities may include light walking, stretching, and lifting light weights [60]. Moderate intensity activities range between 3-6 METS requiring more oxygen consumption and may include brisk walking, stair climbing, and sports involving catching and throwing [60]. Vigorous physical activities are 6 METS or higher. These activities require higher amounts of oxygen consumption to participate, and some examples of include running 5mph or faster, basketball, volleyball, and jumping rope [60].

2.2.3 Physical activity and children with CP

Children with CP have lower levels of physical activity than children who were typically developing [61-63]. The degree to which physical activity is low depends on the level of CP involvement. There is evidence that physical activity is approximately 40 % lower in ambulatory children with CP [64] and 70 to 80 % lower in non-ambulatory children with CP [65, 66] than in typically developing children. In a study by van Eck et al. [67, 68], 89 % of Dutch adolescents with CP were not physically active enough to meet the applied recommended standards of 1 hour of moderate activity for 7 days a week. Similarly, a study conducted by Zwier et al. [69] reported that 92 to 93 % of Dutch children with CP had insufficient physical activity levels and 41 % had lower levels of physical activity than typically developing children.

A variety of issues, such as muscle weakness, low muscle endurance, muscle stiffness, and pain, may make it difficult for children with CP to participate in physical activity [45, 69-71]. Muscle weakness and decreased endurance are major secondary consequences of CP [19, 45, 70, 72]. Moreover, prior research reported that more than 30 % of children with CP across all GMFCS levels experience pain, with higher pain levels associated with lower participation in physical activity [73, 74].

2.2.4 Importance of physical activity in children with CP

Physical activity is important because higher levels are associated with a lower risk for developing chronic diseases, such as cardiovascular disease, type 2 diabetes mellitus, obesity, and osteoporosis [66, 75-78]. Participation in physical activity is particularly important during childhood when the musculoskeletal and the cardiorespiratory systems are developing and chronic diseases begin to emerge [69, 70]. Children with CP have small and underdeveloped bones [64, 79] and muscles [3, 65, 80, 81] which is due, at least in part, to their low physical activity [65]. Physical activity is believed to play a significant role in developing bone mass throughout childhood and adolescence [7], and in the maintenance of skeletal mass in young adults [82]. It has also been hypothesized that physical activity plays a critical role in maintaining functional strength and structure of bone [60]. The intensity of the physical activity and the degree of stress applied to the bone may be significant factors regarding the maintenance of bone density [83]. Furthermore, given that bone structure and function may change with varying loading, physical activity is the most significant influence on bone [84]. The development of a robust adult musculoskeletal system is important to prevent future osteoporotic fractures, which is a major issue due to decreasing mechanical loading and physiological stimulus during childhood and adolescence [76, 81]. These considerations demonstrate the need to engage in physical activity throughout one's life, especially during childhood.

Children with CP already have a disadvantage in terms of acquiring acceptable levels of physical functioning because their bones, muscles, and cardiorespiratory systems are not fully developed at birth, causing slowed progression for growth [70]. Children with CP may not be able to reach their full potential in motor tasks if they do not have enough fitness capacity, resulting in limited participation in daily physical activities [85]. Furthermore, low levels of physical fitness may limit their functional independence and put them at risk for sedentary behavior [77].

2.2.5 Physical activity and jumping

Plyometrics are a type of exercise that combines aerobic and resistance training. Jumping jacks and other plyometric workouts are designed to help people run faster and jump higher due to rapid stretching and shortening of the muscles during the eccentric and concentric phases of the movement [86]. Movement can become more explosive by stressing the muscles in this eccentric and concentric sequence, increasing both strength and agility for sports that need multidirectional movement, such as basketball, volleyball, and American football [6].

In plyometric exercise, a sudden stretch of a muscle is followed by rapid shortening [87]. The stretch-shorten cycle is one of the most common types of muscular action during locomotion. It occurs when active muscle stretching is followed by active muscle shortening when subjected to impact or stretch forces [88]. The stretch-shorten cycle is used in plyometric exercise to train muscles to accomplish more work in less time [89, 90]. Muscles swiftly convert from an eccentric to a concentric motion in various plyometric activities, effectively leaving little time for the muscles to relax. The stretch reflex and the muscles' stored elastic energy combine to allow the muscle to generate more force [89]. Repeated plyometric training conditions the brain stem to respond more quickly to the stretch-shortening cycle [87]. When compared to traditional resistance training, this sort of exercise also creates more muscular strain. As a result, plyometric activities are frequently recommended for improving jumping velocity [89]. Plyometric training has been known to improve vertical jump performance in adult [6, 89, 91], pubertal [92], and prepubertal [93] populations.

This form of plyometric training can improve a child's speed of movement, power output [6, 93, 94], and bone strength [95]. Adults and pubertal children have been shown to benefit from plyometric training programs for boosting running speed, jumping ability [96], and strength [6]. Although strength training helps increase muscle function and coordination among muscle groups, children benefit more from practicing and perfecting sport abilities – particularly activities that are performed more quickly and generate more power [97]. As a result, plyometric training may be an effective intervention for strengthening children's motor abilities to run, jump, hop, skip, and providing them with the foundation to engage in physical activities that have greater reliance on power generation for optimal participation.

2.2.6 The importance of participation in jump and plyometric exercise for children with CP

Physical fitness [4], physical activity [5], and participation in organized recreational and play activities [98] are all lower among children with limited motor competence. Jumping is a key skill for involvement in active games and sports [5]. Additionally, jumping can show major benefits for young children including strengthening core muscles [6], as well as improving coordination, balance, posture, flexibility [10], and metabolic rate [11]. There is also evidence that jumping is beneficial to bone health in children [7-9]. As a result, enhancing physical fitness, increasing physical activity levels, and promoting involvement in recreational and play activities in children with low motor competence may be a suitable intervention. However, studies identifying ways to increase jump performance in children with limited motor skills, such as children with CP, are lacking.

Strength training has been indicated to be a successful therapeutic strategy for enhancing muscle strength and motor function in children with CP [99]. Strength training was previously advised with caution for CP, with the belief that the massive exertion would correspondingly aggravate muscle stiffness and spasticity [100]. However, recent observations have revealed that strength training does not increase spasticity [29, 101]. Although the benefits of strength training for children with CP are clear, the benefits of power-based activities, such as jumping, may be greater. Furthermore, it has been suggested that jumping and plyometric workouts may have a beneficial effect on musculature in children with CP, including improvement in the integrity of muscle torque-generating capacity [102, 103]. Plyometric workouts can produce high-velocity dynamic movements, as well as high impact forces on muscles and bones [6]. Prior research has also shown that plyometric exercises could be included to the physical rehabilitation programs of children with CP to increase muscle strength and walking performance [103]. Children with CP may be able to limit the negative effects of physical inactivity by participating in exercises like jumping [71].

2.3 Vertical Jump

2.3.1 An overview of the vertical jump

The vertical jump can be defined as a complex series of ballistic multi-joint actions where the muscles around the ankle, knee, and hip joint collectively operate to produce patterns of movement [104]. Jumping is a simple plyometric action that is necessary in a variety of sports.

The goal of the vertical jump is to generate enough force to lift the body's mass to its maximum elevation [105], then land feet first and in balance [106-108]. When it comes to vertical jump, force refers to an individual's maximal strength, while velocity refers to an individual's maximum speed [109]. Additionally, the vertical jump height improves if there is an increase in strength and velocity in relation to body weight. A jumper's mass and the linear impulse, which is the consequence of the upward acceleration on the various body segments engaged in the jumping movement, determines a jumper's velocity during [110].

The achievement of maximum vertical displacement and successful injury prevention through impact absorption are two of the most important aspects of the vertical jump [15, 111]. The latter is based on muscle flexibility as well as deep eccentric contractions of the lower limbs in order to extend the duration and angular space over which the impact force is reduced. Understanding extrinsic elements, such as excessive ground reaction force, are also essential in prevention of vertical jump injuries [15]. When landing from a jump, excessive ground reaction force can cause lower extremity injury [106]. It is critical to understand how feedback affects ground reaction force and can potentially lessen risk of injury. The combination of peak forces during the landing phase of the jump and the high frequency of jumps in vigorous physical activity results in a significant amount of stress in the lower limb joints, which can lead to injury [111]. In most two-footed landings, there are usually two peak forces (F1 and F2), the second of which is usually related to risk of injury [15]. The forefoot and rear foot contact peak forces are represented by F1 and F2, respectively. F1 is the impact spike that happens roughly 10 milliseconds after the forefoot makes contact with the ground. In activities like spike-jump landings, F2 is the peak associated with rear foot impact and usually occurs within 40-70 milliseconds of ground contact [15]. It has been demonstrated that while increasing the time F2 appears reduces F2, the overall impact absorption time decreases [111].

Two common vertical jump tests include the squat jump and countermovement jump. Because of the relatively short duration of execution, both jumps are frequently used to evaluate the ability to rapidly develop force during dynamic movements [112]. During the squat jump, the individual descends into a semi squat position and holds this position for approximately 3 seconds before takeoff [112]. This measures the ability to quickly develop force during the concentric movement only [113] for the purpose of prescribing and controlling training loads [114, 115]. During the countermovement jump, the individual starts from a standing position and initiates a downward movement, followed immediately by an upward movement leading to takeoff [112, 116]. This provides an assessment of the ability to quickly produce force in the stretch-shorten cycle relying on the contractile abilities that supply elastic energy in working muscles [86, 117]. Countermovement jumps result in higher jump heights compared to that of a squat jump in various populations including athletes and children [112].

2.3.2 Biomechanical assessment of the vertical jump

Biomechanics is a field of study in which movement is assessed and recommendations are made to improve an individual’s performance. Force plates and motion capture systems can be employed in laboratories to collect data on the kinetics (forces over time) and kinematics (movement over time) of movements [118]. Force plates are often used in laboratories to measure forces, such as ground reaction force, and to assess postural stability, explosive force, and power [119]. Force transducers are built into the force plates and measure force in performance planes: vertical, anterior-posterior, and mediolateral. Kinetic data collected in each of these planes can use these planes to assess performance during a variety of gait and jumping actions to further understand postures and movements, which can aid in diagnostics and rehabilitation [119].

The calculation of angular power production around the hip, knee, and ankle joints is possible with the integration of GRF and motion capture data [120]. Joint power is a crucial kinetic variable that is measured during vertical jumping. Peak power is a combination of strength, velocity, force, and neuromuscular adaptations that accounts for the largest output or creation of work over a certain period of time [121]. When a muscle delivers force while also shortening simultaneously, it creates mechanical energy. This is derived by multiplying the joint moment by the angular velocity of the muscle [122]. Joint power is typically normalized by body weight when considered for adolescent populations [123]. Considering their strong relationship, maximizing an individual's power generation may be crucial to their jump performance [124-126]. Prior research has supported that power generation deficiencies and asymmetries in children with CP gait [127], however they have not been studied during jumping.

Marker-based and marker-less systems are the two types of optical motion tracking systems used to assess the kinematic aspects of movement [128]. The location of joints and the orientation of body segments are determined using three-dimensional localization of passive and active markers that are fixed on the individuals' bodies and captured by a calibrated multi-camera video system, according to recent technological standards [129]. Instead of directly tracking human body postures, these systems use fiducial points or landmarks to recognize common object features in successive photos, which are then used to track the movements of a sequence of rigid bodies coupled by rotating joints [128]. An example of a kind of movement is a joint moment, which is determined as the product of two measurable quantities: 1) the moments of inertia of the joint segments, which requires knowledge of the segments' masses and lengths, and 2) the joint's angular acceleration [128].

Each of the three planes of motion (sagittal, frontal, and transverse) are rotated around an axis. The movement takes place in an imaginary plane of motion perpendicular to the imaginary axis of rotation, which intersects at a right angle. The anteroposterior axis, the mediolateral axis, and the longitudinal axis are the three axes of rotation, just as there are three planes of motion. In these axes, joints rotate, providing movement in these planes [130]. Three-dimensional kinematics is a popular approach for calculating joint angles in an XYZ cardan rotation sequence [131]. On the sagittal plane, x is the mediolateral axis of rotation indicating movements of: 1) hip flexion/extension, 2) knee flexion/extension, and 3) ankle dorsiflexion/plantarflexion. On the frontal plane, y is the anteroposterior axis of rotation indicating movements of: 1) hip adduction/abduction, 2) knee adduction/abduction, and 3) rearfoot inversion/eversion. On the transverse plane, z is the longitudinal axis of rotation indicating movements of: 1) hip internal/external rotation, 2) knee internal/external rotation, and 3) ankle adduction/abduction. The femur is measured in relation to the pelvis, the tibia is measured in relation to the femur, and the ankle is measured in relation to the foot [130].

2.3.3 Phases of the vertical jump

There has been significant research identifying phases of the vertical jump including the segment contribution to force production during the jump and take off, coordination of maximal-effort vertical jump motion, contributions of the trunk to standing vertical jump take-offs, and explosive movements from varying positions [132-134]. Other studies have investigated the relationships between the magnitude of ankle, knee, and hip joint moments and power, with the resulting jump performance [120, 135, 136]. Each phase includes notable biomechanical factors that influence the form of the vertical jump. The preparatory phase and landing phase are the two primary phases of the vertical jump [137]. During the jumps preparatory phase, the body's center of mass gets lower and its potential energy decreases. The propulsive segment of this phase occurs when the body pushes down onto the floor to raise the potential energy of all body segments. While the body is airborne, the body is in an unstable state until it comes back into contact with the ground. This is known as the landing phase where all movement is stopped.

The variables found during each phase of the vertical jump are noted in **Figure 1**. The preparatory phase of the vertical jump includes two kinds of movement: eccentric and concentric. During the eccentric phase, the musculotendinous is lengthened prior to contraction where the hip and knees are flexed and the ankles are dorsiflexed to start a squatting movement [88]. When muscles are stretched during this phase, kinetic energy and potential energy is produced through the storage and release of elastic energy which generates force production [133] and increases positive work and power [138]. Muscles that take longer to achieve maximum force in the eccentric phase will produce more ground reaction force [139]. Knee extensors including the rectus femoris and vastus lateralis, for example, have faster ramping-up force due to the type IIb fibers present in fast-twitch muscles [140, 141]. According to prior studies, the extensor muscles of the hip (gluteus maximus and hamstrings) take longer to reach maximal force during the countermovement, lowering knee joint moments with slower cross-bridging during the eccentric phase [109].

During the concentric phase, the musculotendinous unit is shortened to produce a rapid movement. This involves extension of the hips and knees as well as plantarflexion of the ankles [105, 139]. The contraction of these muscles will raise the body's center of mass and lift the legs and thighs off the ground. The relaxation and contraction of muscles in the knees contribute to this movement [137]. Following this propulsive movement, tremendous power and force is created, allowing the body to move [133]. These events are known as the stretch-shorten cycle of the hip, knee, and ankle extensor muscles. This allows the body to move in a more efficient manner that requires less energy than a purely concentric motion (i.e., countermovement jump vs squat jump) [112, 133, 134, 138]. After the body is propelled off of the ground, the body is airborne. This begins after the feet leave the ground when no additional force has been generated. Jump height is determined during this segment of the preparatory phase from the force generated prior to leaving the ground [132]. During the jump, it is critical to prepare for the landing phase of the jump and control the lower extremities to improve cushioning capacity of the lower limbs [15].

The landing phase of the jump begins once feet make contact with the ground again and continues until the body returns to an upright standing position. The main goal of the jumper during the landing phase is to slow or stop the body's vertical, horizontal, and sideways motion [15]. To avoid injuries, it is vital to cushion the impact forces by plantarflexion of the ankles and flexion of the knees and hips, with the knees over the toes. The knees final angle should be close to 90 degrees, but not exactly parallel to the floor [106]. It is important to note that, deeper knee angles of more than 90 degrees have been linked to knee injuries including patellar tendonitis [142]. Additionally, if the knees are overly stretched during impact, flexion is forced, causing stress on the patellar tendon [143-145]. The energy associated with landing is also thought to be absorbed by passive (bone, ligament) and active (muscle) tissues [146]. Landing biomechanics that absorb more total sagittal-plane energy during the initial impact phase of landing have been linked to a higher risk of anterior cruciate ligament (ACL) injury. This is due to sagittal-plane knee kinematics and impact forces that are likely to increase ACL stress when landing with greater sagittal-plane energy absorption within the first 100-milliseconds after ground contact [147]. Additionally, the increased internal knee adductor moments caused by frontal knee adductor collapse (i.e. dynamic knee valgus) during landing have been recognized as major factors predisposing ACL injury [148]. Increased rearfoot inversion has also been identified as a significant risk factor for lateral ankle sprain injuries in individuals with chronic ankle instability and neuromuscular impairments [149]. This is significant as lateral ankle sprains are the most prevalent musculoskeletal injury in sports, and occur more frequently in sports that involve jumping [150].

2.3.4 Performance Outcomes

The vertical countermovement jump is a popular performance test for evaluating athletic ability. Some of the primary variables that impact jump performance include takeoff velocity, power, maximum force created by the musculature involved, and the neuromuscular coordination of the upper and lower body segments [132, 137, 151, 152]. When synchronized, lever-like movements generate rotating torques that are converted into rectilinear motion, and takeoff velocity is one of the most significant elements. To achieve ideal projection, relative parts of the body must be located closer together to achieve optimal jump form [153]. This form is achieved through standing with the feet shoulder-width apart, knees slightly bent, neutral head and neck position, and shoulders squarely over the hips [154]. Furthermore, it has been demonstrated that eccentric countermovement jumps regularly produce better results and increased jump height than squat jumps [105, 109, 112, 155, 156]. This is due to the accumulation of elastic energy in the Achilles and patellar tendons, which is then released, resulting in higher angular acceleration [112]. However, torques cannot be efficiently transferred into rectilinear motion without balance and control because some of the force may contribute to other forms of movement. For example, without proper balance, the center of gravity may travel beyond the base of the body, causing horizontal displacement [128]. This is important to note in populations with limited motor control, including children with CP [157-159].

The enhanced takeoff velocity is the result of a complicated chain of events that causes energy to be transmitted throughout the body during the later stages of the jump [160]. This energy is derived from surplus energy stored in the hips and is mostly used for three purposes. First, it is used to increase kinetic and potential energy, as well as torque. Second, the muscles and tendons that surround the ankles, knees, and hip joints store and release energy. Finally, an upward pull acting on the trunk at the shoulder is used to pull up on the body when the vertical net joint force at the shoulder is beyond the neutral position, thus increasing the kinetic energy throughout the body [161].

During the vertical jump, it is critical to keep one's head straight above the body rather than forward or backward [162]. This means that more of the body's mass is above the ground reaction force generated when the legs are pressed into the ground. If the ground reaction force is acting perpendicular to the ground, the closer these two objects are aligned and the more force can act to shift the body mass vertically rather than into other planes [137]. This is critical for gaining the most height out of the jump. If the center of gravity and the ground reaction force produced are misaligned, torque is created, which spins the center of gravity, causing translation of the body mass in planes other than vertical [162]. This would then cause a reduction of the maximum height obtained.

Jumpers may find it advantageous to modify their technique during the preparatory phase of the jump to increase performance. Increased jump height is partially dependent on the degree of hip and knee flexion and ankle dorsiflexion achieved during eccentric countermovement in the preparatory phase. This means that these joints can travel a higher angular distance during takeoff, lengthening the time period during which force is generated and perhaps increasing the amount of force produced overall [163]. Rate of force development can also be increased by increasing knee flexion in the beginning position followed by a quick triple extension, which is extension of the hips, knees, and ankles [164]. To improve force output, participants should descend to an angle closer to 90 degrees during the prep phase [15]. This angle is also important to avoid putting undue strain on the knees [144]. Prior research has linked increased knee flexion at a range of 78-85 degrees to increased jump height [134, 137], but it has also been suggested that deeper squats can disrupt segment timing during the jump, therefore negatively affecting performance [163]. Hence, the effect of the degree of knee flexion during the preparatory phase on jump performance is unclear and may be individual-dependent. In this study, while TD children exhibited knee flexion similar to the preferred range at approximately 87%, children with CP exhibited 67% lower knee flexion than the preferred range.

While airborne, another facet of proper jump technique comes into play. To keep the limbs still and parallel as the participant goes through the air, there should be minimal body segment movement [151]. This is significant because jumpers lose their ability to create upward velocity once they leave the ground. Stabilizing body movement ensures that the initial upward momentum is not converted into linear and rotational movement in any other planes [151]. The slight movements while airborne are mostly made after reaching peak height and throughout the descent, which aids in maintaining equilibrium allowing for a more secure and synchronized landing [137].

The technique of the landing phase is primarily focused on proper absorption to reduce risk of injury [15]. The ankles should be plantar flexed and the knees should be fully extended but not locked while making contact with the ground [153]. This is beneficial because it increases the angular distance these joints may travel while reducing momentum and maximizing the capacity to do so. This means that the impact force can be diffused over a longer period of time. This is significant because as the limbs make contact with the ground, less force is applied to them over time [151]. This helps to reduce the risk of injury upon landing, as does avoiding locking the knees into extension, which can be dangerous when landing safely [15]. In order to achieve a broader range of motion through the joints as one slows down, it is recommended to sink further into the knees during landing. Increased time spent during the landing phase should result in less peak forces acting on the body frame, hence increasing the landing's safety [137].

Summary

Cerebral palsy is a disorder associated with profound motor deficiencies, resulting in significant muscle weakness and a limited muscle power generation [3]. These impairments, combined with poor muscular function, contribute to a lack of physical fitness [4] and participation in physical activity [5]. Jumping is an important skill in many physical activities as it promotes muscle [6] and bone growth [7-9]. Furthermore, plyometric jump training helps children improve their coordination, balance, posture, flexibility [10], and metabolic rate [11]. Unfortunately, no studies have evaluated the jumping ability or the biomechanical factors associated with jumping in children with CP.

CHAPTER 3

JUMP PERFORMANCE AND ITS RELATIONSHIP WITH LOWER BODY JOINT KINETICS AND KINEMATICS IN CHILDREN WITH CEREBRAL PALSY

Introduction

Cerebral palsy (CP) is a permanent disorder of movement and posture that stems from a non-progressive injury or malformation of the brain [2, 19, 20]. Cerebral palsy occurs in approximately 3.2 per 1000 live births, and is one of the most common causes of motor deficiency in young children [1, 16]. In addition to substantial deficits in motor control, children with CP have significant muscle weakness and limited ability to generate muscle power [3]. The poor muscle performance is linked to small muscles that have a high concentration of non-contractile protein [165] and fat [64, 65]. Deficits in motor control coupled with poor muscle performance is surely a major contributor to the low physical fitness [4], physical activity [5], and participation in organized recreational and play activities [98] of children with CP, as well as the underdevelopment of their bones [166] and associated increased risk of fracture [167]. Physical activity is 50 to 80 % lower in children with CP than in typically developing children [64-66]. Thus, it is imperative to find ways to enhance physical fitness, increase physical activity levels, and promote activity in children with low motor competence.

One skill that is necessary for participation in many physical activities and offers the stimulation to the musculoskeletal system that can promote strengthening of muscle [6] and bone [7-9] is jumping. Jumping involves the production of high-velocity dynamic movements through rapid muscle contraction, leading to high impact forces on bones [5, 6]. There is also evidence that exercise training that involves jumping or other plyometric activities increases running speed and jump height, which may be due to rapid stretching and shortening of the muscles during the eccentric and concentric phases of the movement [168]. Moreover, jump training has been linked to improved coordination, balance, and posture [10], and greater flexibility [10] and metabolic rate [11] in children. Unfortunately, because children with CP are unable to jump or have limited jumping ability, they are unable to fully participate in activities that require jumping or benefit from the health advantages associated with jumping. Despite the obvious benefits of jumping, studies identifying ways to increase jump performance in children with CP or other movement disorders are lacking. One potential reason for the oversight is the absence of studies providing a kinematic and kinetic assessment of jump performance in children with CP. Thus, biomechanical factors contributing to the limited jumping ability of children with CP are unclear.

The primary aim of this study was to determine if there is a deficit in jump performance in children with CP. It was hypothesized that children with CP would have lower jump height compared to typically developing children. Another aim was to determine if the expected deficit in jump performance in children with CP is related to discrepancies in their lower body joint kinetics and kinematics. It was hypothesized that the expected low jump height in children with CP would be related to low power generation, low flexion and extension, and low ROM at the hip, knee, and ankle during jumping.

Methods

Participants

Ambulatory children with spastic CP aged 5 to 11 who are being recruited from the Children's Healthcare of Atlanta, public schools throughout the state of Georgia, social media platforms, pediatric rehabilitation centers throughout the southeast region of the United States, and the Cerebral Palsy Foundation as part of a randomized controlled trial participated in this study. Typically developing children who were similar in age (± 1.5 y), sex, and race, and between the 5th and 95th sex – and age-based percentiles for height and body mass to the children with CP and not participating in high-level sports were recruited from Athens and Atlanta, Georgia, and surrounding communities through the use of flyers, postcards, and word of mouth..

Before their child's involvement in the study, parents or guardians provided written informed consent, and children, if able, provided informed assent. Exclusion criteria includes prior fracture in both femurs or tibias, currently taking bisphosphonates, unable to stand independently, orthopedic surgery within the last six months, children with pure athetoid CP, baclofen pump in the abdomen, and botulinum toxin treatment within the last year. The University of Georgia Institutional Review Board has approved the project.

Anthropometrics

Participant height and body mass was measured while the children are in a t-shirt and shorts without shoes or braces. Height was measured to the nearest 0.1 cm using a stadiometer (Seca 217; Seca GmbH & Co. KG., Hamburg, Germany). Body mass was measured to the nearest 0.2 kg using a digital scale (Detecto, 6550, Cardinal Scale, Webb City, MO). Body mass index (BMI) was calculated based on height and weight. Normative data published by the

Centers for Disease Control and Prevention [169] as used to determine age- and sex-based percentiles of height, body mass, and BMI.

Sexual Maturation

Sexual maturity for each participant was assessed by their parent or guardian using the Tanner staging technique [170]. Signs of pubic hair and breast development was assessed in girls and pubic hair and testicular/penis development was assessed in boys. Ratings range from I to V, with I indicating no signs of sexual development and V indicating full development.

Gross Motor Function

Gross motor function was assessed by a trained healthcare professional using the Gross Motor Function Classification Scale (GMFCS). The classification system ranges from I to V. A classification of GMFCS I and II are independently ambulatory, but have a reduced gait speed; GMFCS III achieve mobility through the use of assistive walking devices; and GMFCS IV and I achieve mobility through the use of a wheelchair [50]. This study included children classified as GMFCS I or II.

Jump Performance

Study participants performed 3 vertical countermovement jumps interspersed with approximately 45 second recovery periods. Participants stood in an upright position for 5 seconds before and after the trials. Prior to the initial trial, participants were instructed to stand upright with their feet shoulder-width apart and hands on their hips. The participants were told to not take any additional steps before and after jumping. Hands remained on the hips during the entire jump. Exclusion criteria for each jump trial included taking extra steps before the preparatory phase and after landing, incorrect countermovement form (i.e., sustaining a squat for more than 3 seconds), and inability to complete more than one trial.

Kinetic Analyses

Two adjacent strain gauge force platforms (100 Hz; Bertec, Columbus, OH) were used to record the kinetic data relating to force during each jump trial. All force platforms were the same level as the ground. The data obtained with the force platforms was used to calculate joint power:

$$Power_{joint} = \frac{moment_{joint} * angular\ velocity}{body\ mass}$$

The kinetic data collection was synchronized through the Qualisys system (Qualisys, Lincolnshire, IL). Hip, knee, and ankle joint power was calculated using Visual 3D (C-Motion, Inc., Germantown, MD) for the more (MAL) and less affected limbs (LAL). A 14 Hz 4th order zero-lag Butterworth lowpass filter will be used to filter jump data [171].

Kinematic Analyses

Prior to data collection, 53 passive reflective markers of 12.7 mm diameter were placed on each participant and adjusted to the CAST_Static_Full_Body and CAST_Dynamic_Full_Body model (Qualisys, Lincolnshire, IL). A synchronized 3D optical motion capture system consisting of 1 HD camera and 9 infrared cameras (100 Hz; Qualisys, Lincolnshire, IL) was used to capture kinematic jump data. In order to obtain the trajectories of the markers during the jumps, all kinematic data was reviewed, gap-filled using a polynomial method, and smoothed with a 5 s moving window. Subsequently, the trajectories and the dynamic full body AIM model were used to calculate the joint angles from the positions of the markers. Kinematic data were processed through Visual 3D (Germantown, Maryland) where a 4^{th} order, 14 Hz Butterworth filter was applied [171]. Knee and ankle joint angles were calculated in the sagittal plane for both the more (MAL) and less (LAL) affected limbs. The MAL and LAL's jump data will be divided into two phases: preparatory phase and landing phase, but only data from the preparatory phase were analyzed for this study. The start of the preparatory phase is noted at the beginning of the trial while standing upright. The moment both feet regain contact with the ground will mark the end of the preparatory phase. The preparatory phase was separated into 4 subphases: 1) upright stance, 2) eccentric, 3) concentric, and 4) airborne. Maximum hip flexion, maximum knee flexion/extension, and maximum ankle dorsiflexion were calculated using data obtained during the eccentric subphase. Maximum hip extension, maximum knee extension, and maximum plantarflexion were calculated using data obtained during the concentric subphase. Jump height was calculated using center of mass data obtained during the airborne subphase. The calculation is below:

$$Jump\ Height = Center\ of\ Mass_{max} - Center\ of\ Mass_{initial}$$

The time of take-off (initial) was determined once the final toe marker does not have contact with the ground. The average of the values of each variable in the three trials is reported.

Statistical Analysis

IBM SPSS Statistics 25 was used to conduct all statistical analyses. Skewness and kurtosis will be used to determine normality. Variables with skewness and kurtosis values less than 2 were considered normally distributed. Group differences in kinetic and kinematic variables in the MAL and the LAL throughout the preparation were assessed using independent samples t-tests for normally distributed data and Mann-Whitney U tests for nonnormally distributed. Relationships between (1) kinematic variables and physical activity and (2) kinetic variables and physical activity were assessed using Spearman rho correlation tests. All tests were two-tailed and the alpha level will be set at 0.05. Group differences with *p* values between 0.05 and 1.0 were viewed as marginally insignificant. Cohen's d (*d* = mean difference between groups/pooled SD) were used to determine the magnitude of the effects, with 0.2, 0.5, and 0.8 signifying small, medium, and large effect sizes, respectively [172].

Results

Physical Characteristics

Physical characteristics are reported in **Table 1.** Seventeen children with CP and 17 control children, 5 to 11 years of age, and matched for age, sex, and race were included in the study. As planned, there were no group differences in age, sex, or race ($p > 0.780$). There were also no differences in height, body mass, or BMI, or their percentiles ($p > 0.330$).

Group Comparisons of Jump Performance, Joint Kinetics and Joint Kinematics

Jump height of children with CP compared to controls is presented in **Figure 2**. Children with CP had 38 % lower jump height ($d = 1.243$, $p = 0.001$). Joint power generated during the jump in children with CP compared to controls is presented in **Figure 3**. Children with CP had 44 % lower knee joint power in the MAL ($d = 1.204$, $p = 0.002$), 47 % lower ankle joint power in the MAL ($d = 1.667$, $p < 0.001$), and 30 % lower ankle joint power in the LAL ($d = 1.078$, $p = 0.002$). Children with CP also had 29 % lower hip joint power in the MAL, though the difference was marginally insignificant ($d = 0.524$, $p = 0.067$).

The degree of joint flexion and extension in the sagittal plane in children with CP compared to controls is presented in **Figure 4**. During the eccentric subphase of the jump, children with CP exhibited knee flexion that was 23 % lower in the MAL (d = 1.628, $p < 0.001$) and 15 % lower in the LAL (d = 1.077, p = 0.004), and ankle dorsiflexion that was 35 % lower in the MAL (d = 1.490, $p < 0.001$). Children with CP also exhibited 17 % lower hip flexion in the MAL, but the difference was marginally insignificant (d = 0.631, p = 0.076). During the concentric subphase of the jump, children with CP exhibited and ankle plantarflexion that was 58 % lower in the MAL (d = 1.737, $p < 0.001$) and 51 % lower in the LAL (d = 1.662, $p < 0.001$). Children with CP also exhibited knee extension that was 13 % lower in the MAL (d = 0.618, p = 0.102) and 16 % lower in the LAL (d = 0.490, p = 0.163), though the differences were marginally insignificant.

In the sagittal plane, children with CP had lower ROM in the MAL and LAL hip (d = 1.512, $p < 0.001$ and d = 1.181, p = 0.002, respectively), knee (d = 2.066, $p < 0.001$ and d = 1.428, $p < 0.001$, respectively), and ankle (d = 3.378, $p < 0.001$ and d = 1.618, $p < 0.001$, respectively).

Relationship Between Jump Height and Joint Kinetics

Scatter plots representing the relationships between jump height and joint power are presented in **Figure 5**. Jump height was positively related to hip, knee, and ankle power generated in the MAL of children with CP (r range = 0.522 to 0.645, $p < 0.05$) and hip power (r = 0.596, p = 0.012) and ankle power (r = 0.652, p = 0.005) generated in the MAL of controls. Jump height was also positively related to knee power (r = 0.713, p = 0.001) and ankle power (r = 0.853, $p < 0.001$) generated in the LAL of children with CP and ankle power (r = 0.525, p =

0.031) generated in the LAL of controls. Though jump height was also positively related to knee power (r = 0.473, p = 0.055) generated in the MAL, as well as hip power (r = 0.434, p = 0.082) and knee power (r = 0.473, p = 0.055) generated in the LAL of controls, the relationships were marginally insignificant.

Relationship Between Jump Height and Joint Kinematics

Scatter plots representing the relationships between jump height and the degree of joint flexion and extension in the sagittal plane of the MAL are presented in **Figure 6**. Jump height was positively related to the degree of knee flexion during the eccentric subphase of the jump in children with CP (r = 0.708, p = 0.001). Jump height was positively related to the degree of knee flexion during the eccentric subphase of the jump in controls, though the relationship was marginally insignificant (r = 0.453, p = 0.068).

The relationships between jump height and the degree of joint flexion and extension in the sagittal plane of the LAL are presented in **Figure 7**. Jump height was positively related to the degree of knee flexion (r = 0.652, p = 0.005) and ankle dorsiflexion (r = 0.561, p = 0.021) during the eccentric subphase of the jump, and negatively related to the degree of plantarflexion (r = -0.586, p = 0.013) during the concentric subphase of the jump in children with CP. Jump height was negatively related to the degree of plantarflexion (r = -0.529, p = 0.029) during concentric subphase of the jump in controls.

Jump height was positively related to knee and ankle ROM in the sagittal plane in the MAL of children with CP (r = 0.502 and 0.500, respectively, both $p < 0.05$) and controls (r = 0.493 and 0.500, respectively, both $p < 0.05$). Jump height was positively related to knee and ankle ROM in the LAL of children with CP (r = 0.672 and 0.735, respectively, both $p < 0.05$).

Additionally, jump height was positively related to hip ROM in the LAL of children with CP ($r = 0.439$, $p = 0.078$) and to knee ($r = 0.444$, $p = 0.074$) and ankle (0.471, $p = 0.057$) ROM in the LAL of controls, though the relationships were marginally insignificant.

Summary of jump performance and the associated kinetic and kinematic biomechanical markers of children with CP and controls is presented in **Figure 8**.

Discussion

This is the first study to assess vertical jump performance of children with CP. The primary observation was that ambulatory children with CP have a lower vertical jump height compared to typically developing children. Specifically, jump height was almost 40 % lower in children with CP compared to controls. Further, knee and ankle power generation in the MAL were more than 40 % lower in children with CP compared to controls. The children with CP also had lower power generation in the LAL, though the magnitude of the deficit was less and limited to the ankle. In addition, children with CP exhibited lower hip, knee, and ankle ROM in the MAL and LAL during the preparatory phase of the jump cycle compared to controls, but the deficits were greater in the MAL. The low ROM in the knee and ankles was attributed to reduced knee flexion and dorsiflexion, respectively, during the eccentric subphase of the jump and reduced knee extension and plantarflexion, respectively, during the concentric subphase. The lower jump height in children with CP was accompanied by low power generation at the knee and ankle and low ROM in the hip, knee, and ankle. The relationships between jump height and power generation were stronger in the knee and ankle than in the hip. Similarly, jump height was positively and significantly related to knee and ankle ROM, but not hip ROM. Overall, the results are important because they suggest that jumping is compromised in children with mild CP and potential kinetic and kinematic contributors have been identified.

Previous studies have assessed vertical jump performance in adult athletes with CP [173-175]. However, until the present study, jump performance and its relationship with lower body kinetics and kinematics had not been evaluated in children with CP. Furthermore, a comparison of jump performance of individuals with CP to a control group has been absent. Nevertheless, the low jump height observed in the children with CP in the present study is consistent with the stated hypothesis and studies of high-level adult football players with CP who had 34 – 61 % lower jump height than jump previously reported for elite football players without CP [176-179].

The low power generated during the vertical jump in children with CP in the present study is consistent with studies of high-level adult football players with CP who generated 41 % less power [175] than power generation previously reported for high-level football players without CP [178]. In addition to the focus on children with CP in the present study, power generation of individual limbs and joints were evaluated. Power generated at the knee and ankle of the MAL were 44 % ($d = 1.204$) and 47 % ($d = 1.667$) lower, respectively, in children with CP than in typically developing controls ($p < 0.05$). Power generated at the ankle of the LAL was also lower in children with CP ($p < 0.05$), although the magnitude was smaller (30 %, $d = 1.078$). No detectable differences were observed at the knee of the LAL or the hip on either side, though the general pattern of low power generation was the same. The more pronounced deficit in power generation at the ankle, especially in the MAL, than at the hip and knee joints of children with CP is similar to what has been reported for poor jumpers when compared to good jumpers [137]. It is also consistent with the more pronounced deficits in the leg muscles than the thigh muscles in adolescents and young adults with hemiplegic CP [180]. This is important because muscle strength is an important component of muscle power.

Jump height in the children with CP was related to muscle power generation in the hip, knee, and ankle in the MAL, and knee and ankle in the LAL. While jump height was positively related to power generated at each joint, the largest group difference was in ankle joint power suggesting that the deficit at the ankle is the greatest contributor to the low jump height in children with CP. However, studies with larger sample sizes are needed to support the application of more sophisticated approaches to understand which joint or joint combination contributes most to the compromised jump performance in children with CP.

In addition to the positive relationship between jump height and joint power, jump height was also related to the degree of knee flexion and ankle dorsiflexion during the eccentric subphase, and ankle plantarflexion during the concentric subphase of the jump cycle. Prior research suggests knee flexion at a range of 78-85 degrees during the eccentric phase of the jump is associated with greater jump height [134, 137], which is similar to the degree of knee flexion in the controls in the present study (average = 87 and 88 degrees). Conversely, the average knee flexion on the children with CP was much lower at 67 degrees. Thus, the lower knee flexion during the eccentric subphase of the jump cycle may have contributed to the low jump height in children with CP in the present study. This idea is supported by the positive relationship between jump height and knee flexion in both limbs. Interestingly, although dorsiflexion was lower during the eccentric subphase and plantarflexion was lower during the concentric subphase of the jump cycle in the MAL of children with CP relative to typically developing children, they were not significantly related to jump height. It is plausible that the ankle motion is no longer contributing to lower body functional performance when its range of motion becomes too restricted.

The present study has limitations that need to be discussed. First, the sample size was small. However, despite this limitation, group differences were detected and the proposed hypotheses were supported, which can be attributed to the large effect sizes for jump height and many kinetic and kinematic measurements. Second, the vertical jump test is limited to children with CP who are ambulatory and can complete a jump. Third, the current sample includes both hemiplegic and diplegic children with CP. While this may be a factor impacting the ability to identify the degree of the impact of CP, all diplegic children in this sample had one side impacted differently than the other, providing the assumption that every child with CP in the study had some degree of asymmetry.

In conclusion, the findings suggest that jump height is lower in ambulatory children with mild CP than in typically developing children. The lower jump height in children with CP is related to their lower power generation and ROM at the ankles and the knees during jumping. Future studies should determine if treatments that target these areas lead to improvement in jump performance in children with CP.

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Figure Legends

Figure 1. The figure demonstrates the preparatory and landing phases of vertical jump cycle. The preparatory phase includes four subphases: A) upright stance, B) eccentric, C) concentric, and D) airborne.

Figure 2. Differences in jump height in children with cerebral palsy (CP) and typically developing children (Con). *Group difference, $p < 0.05$.

Figure 3. Differences in power generation at the hip (A), knee (B), and ankle (C) in the more affected (MAL) and less affected limbs (LAL) of children with cerebral palsy (CP) and typically developing children (Con). *Group difference, $p < 0.05$.

Figure 4. Differences in sagittal angles of the hip, knee, and ankle. Hip flexion (A), knee flexion (B), ankle plantarflexion (C), hip extension (D), knee extension (E), and ankle dorsiflexion (F) in the more affected (MAL) and less affected limbs (LAL) of children with cerebral palsy (CP) and typically developing children (Con). *Group difference, $p < 0.05$.

Figure 5. Spearman rho correlations assessing the relationships between jump height and power generation of the hip, knee, and ankle in the more affected (MAL; A – C) and less affected limb (LAL; D – F) of children with cerebral palsy (CP) and typically developing children (Con).

Figure 6. Spearman rho correlations assessing the relationships between jump height and sagittal angles of the hip, knee and ankle of the more affected limb (MAL) of children with cerebral palsy (CP) and typically developing children (Con). Hip flexion (A), knee flexion (B), and ankle dorsiflexion (C) were measured during the eccentric phase of the jump cycle. Hip extension (D), knee extension (E), and ankle plantarflexion (F) were measured during the concentric phase of the jump cycle.

Figure 7. Spearman rho correlations assessing the relationships between jump height and sagittal angles of the hip, knee and ankle of the less affected limb (LAL) of children with cerebral palsy (CP) and typically developing children (Con). Hip flexion (A), knee flexion (B), and ankle dorsiflexion (C) were measured during the eccentric phase of the jump cycle. Hip extension (D), knee extension (E), and ankle plantarflexion (F) were measured during the concentric phase of the jump cycle.

Figure 8. The figure demonstrates the difference in joint angles during the vertical jump and the deficit in vertical jump height between children with cerebral palsy (CP) and typically developing children (Con). The preparatory phase includes four subphases: upright stance, eccentric, concentric, and airborne. The angles noted in the eccentric phase are hip flexion, knee flexion, and ankle dorsiflexion. The angles noted in the concentric phase are hip extension, knee extension, and ankle plantarflexion. The power generated noted are included in the concentric phase for hip, knee, and ankle.

Tables & Figures

Table 1. Physical characteristics of children with cerebral palsy (CP) and controls (Con)

	CP (n = 17)	Con (n = 17)	*d*	*p*
Age (y)	8.7 ± 2.3	8.7 ± 2.0	0.096	0.783
Sex (M/F)	11/6	11/6	-	-
Race (Caucasian, African American, Asian)	13/3/1	13/3/1		
Tanner stage (I/II/III/IV/V)				
Pubic hair	14/1/1/0/1	14/1/0/2/0	-	-
Breast/testicular	11/5/1/0/0	14/2/1/0/0	-	-
Height (cm)	130.6 ± 15.4	133.4 ± 14.6	0.189	0.585
Height (%)	52.4 ± 38.4	63.3 ± 24.7	0.343	0.337
Body mass (kg)	29.6 ± 9.7	30.8 ± 11.6	0.113	0.946
Body mass (%)	47.5 ± 34.3	54.7 ± 26.0	0.240	0.493
BMI (kg/m^2)	16.9 ± 2.9	16.7 ± 2.9	0.064	0.973
BMI (%)	48.1 ± 34.5	47.8 ± 30.2	0.011	0.975
GMFCS (I/II)	12/5	-	-	-

Values are mean ± SD; % for height, body mass, and BMI reflect the percentile relative to age- and sex-based norms; GMFCS = gross motor function classification system.

Figure 1.

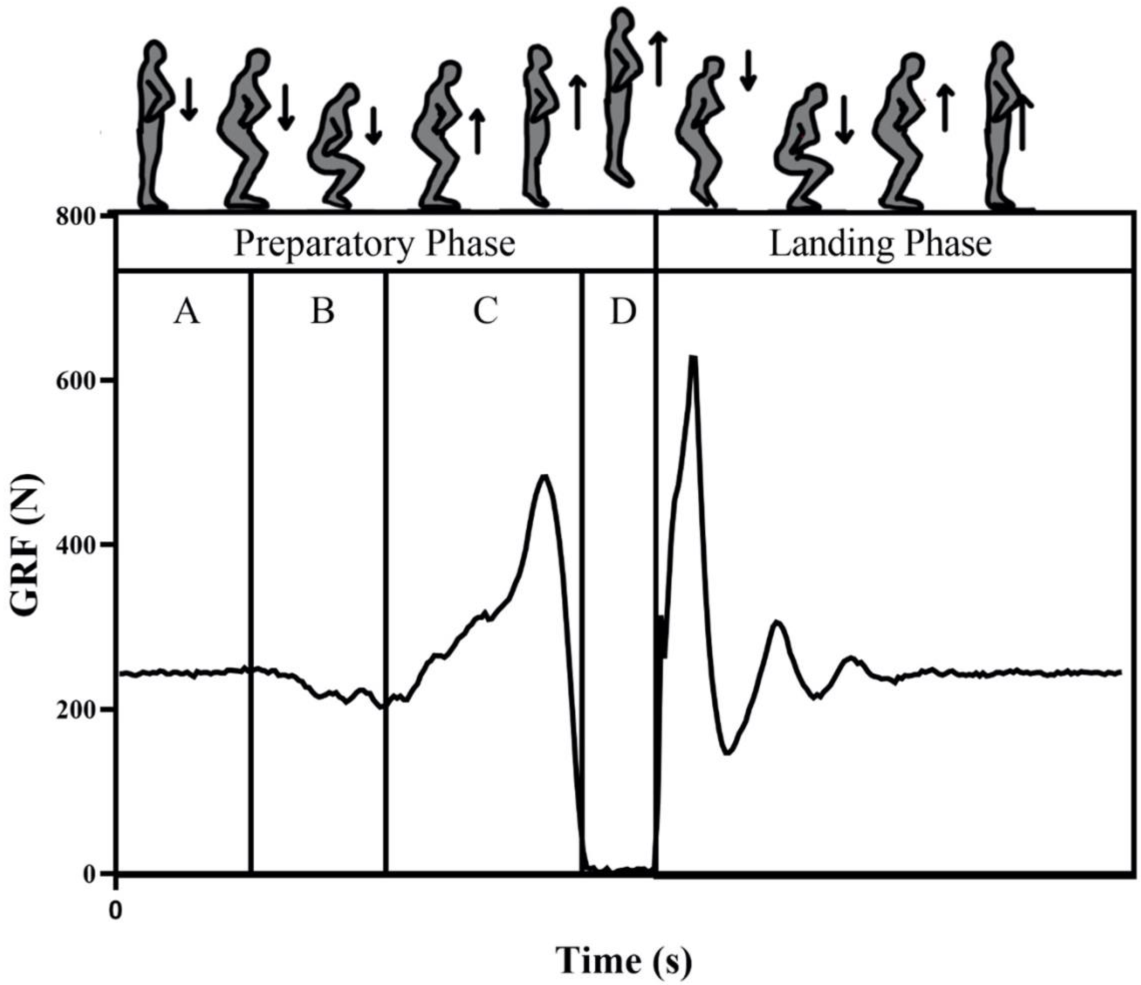

800
600
400
200
0
0
GRF (N)
Preparatory Phase
Landing Phase
A
B
C
D
Time (s)

Figure 2.

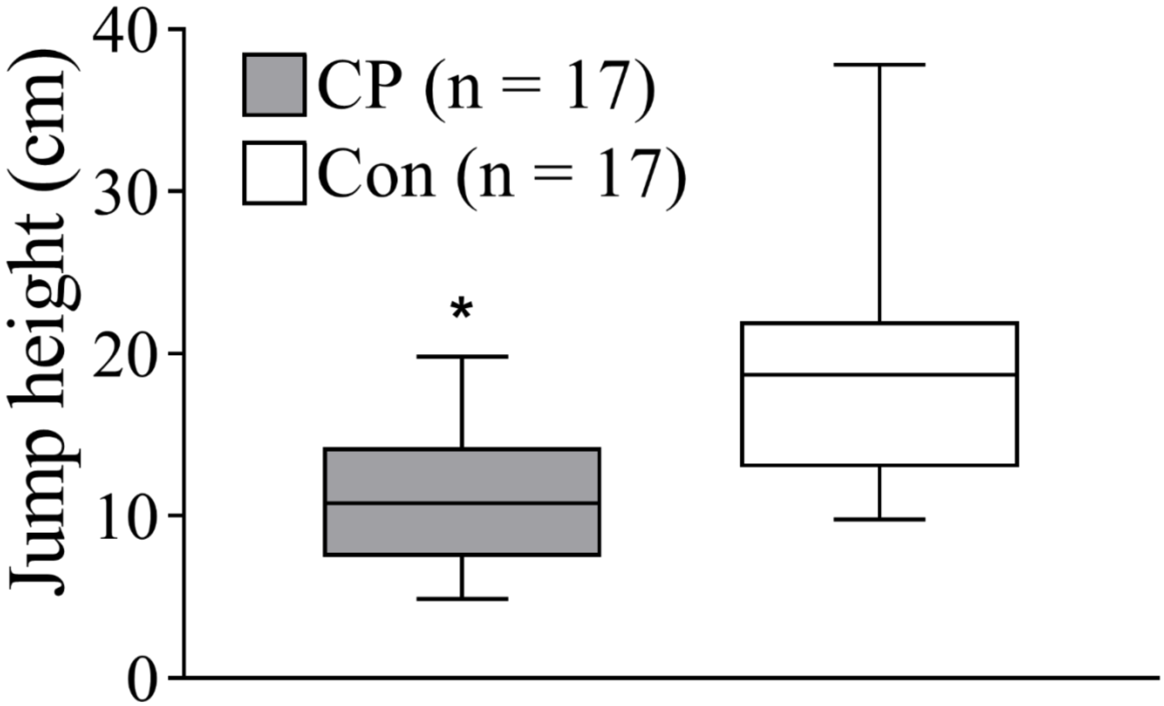


Figure 3.

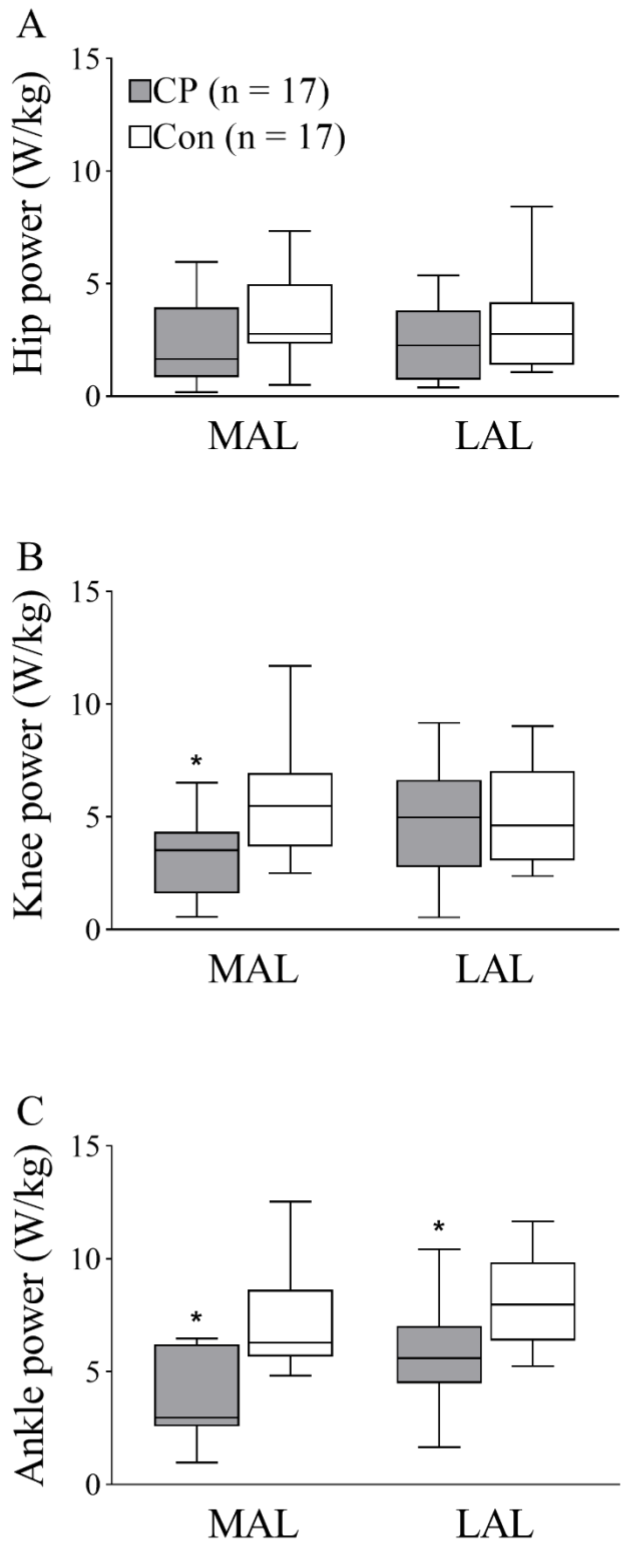
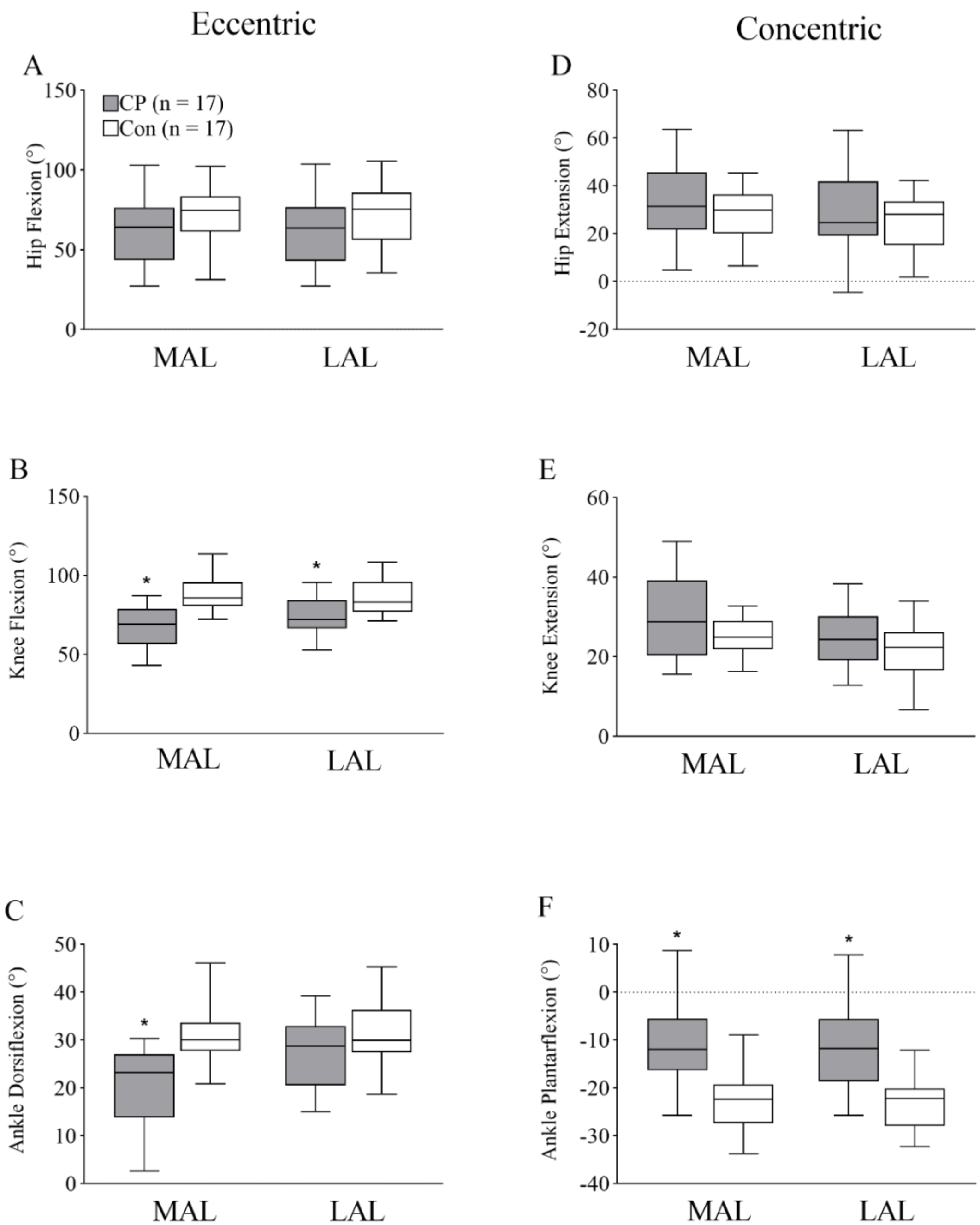

A
15
CP (n = 17)
Con (n = 17)
10
5
0
Hip power (W/kg)
MAL
LAL
B
15
10
5
0
Knee power (W/kg)
*
MAL
LAL
C
15
10
5
0
Ankle power (W/kg)
*
*
MAL
LAL

Figure 4.



Eccentric
Concentric
A
CP (n = 17)
Con (n = 17)
Hip Flexion (°)
150
100
50
0
MAL
LAL
D
Hip Extension (°)
80
60
40
20
0
-20
MAL
LAL
B
Knee Flexion (°)
150
100
50
0
*
*
MAL
LAL
E
Knee Extension (°)
60
40
20
0
MAL
LAL
C
Ankle Dorsiflexion (°)
50
40
30
20
10
0
*
MAL
LAL
F
Ankle Plantarflexion (°)
10
0
-10
-20
-30
-40
*
*
MAL
LAL

Figure 5.

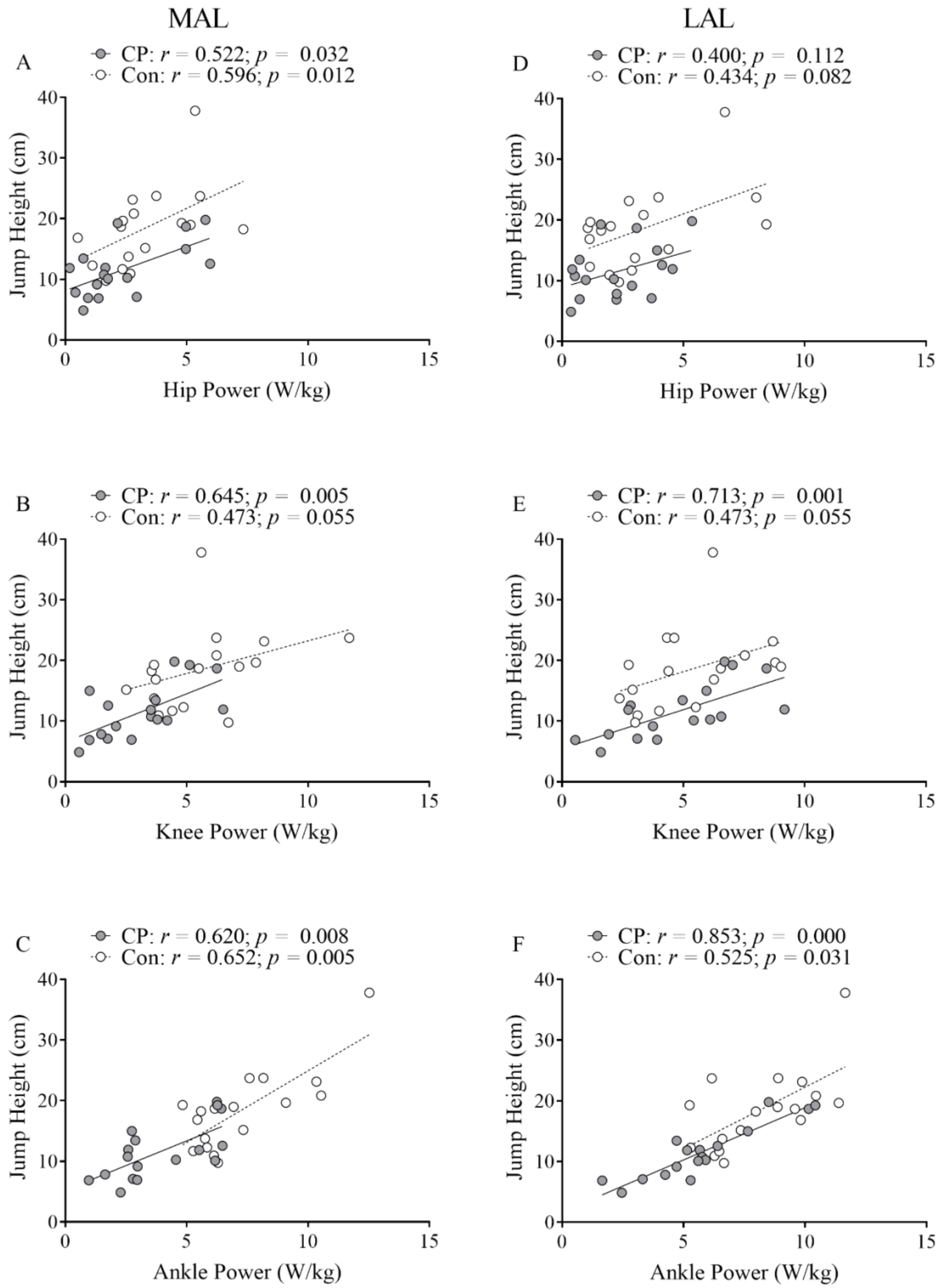

MAL
LAL
A
CP: r = 0.522; p = 0.032
Con: r = 0.596; p = 0.012
D
CP: r = 0.400; p = 0.112
Con: r = 0.434; p = 0.082
B
CP: r = 0.645; p = 0.005
Con: r = 0.473; p = 0.055
E
CP: r = 0.713; p = 0.001
Con: r = 0.473; p = 0.055
C
CP: r = 0.620; p = 0.008
Con: r = 0.652; p = 0.005
F
CP: r = 0.853; p = 0.000
Con: r = 0.525; p = 0.031
Jump Height (cm)
Hip Power (W/kg)
Knee Power (W/kg)
Ankle Power (W/kg)
0
10
20
30
40
0
5
10
15

Figure 6.

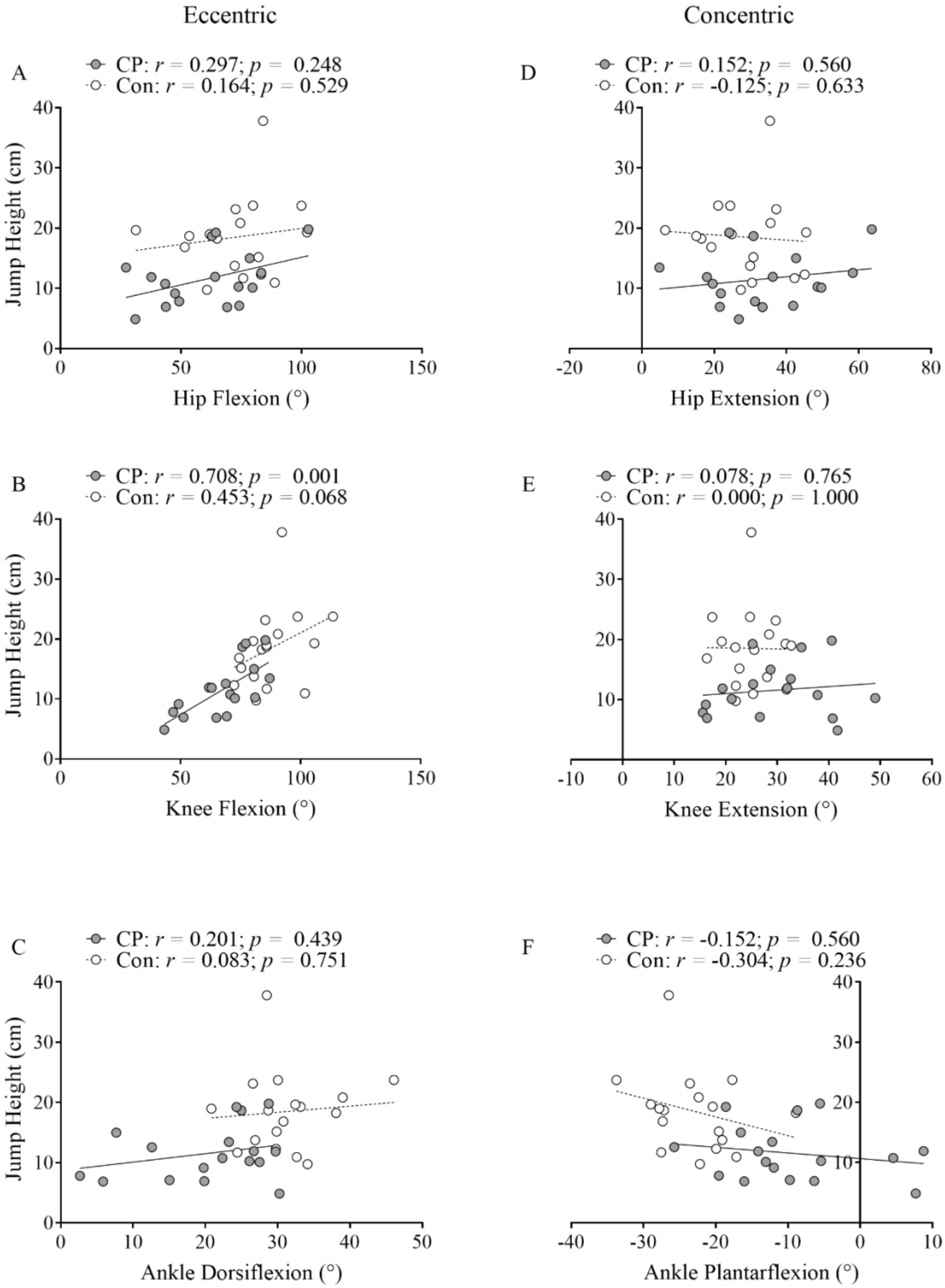
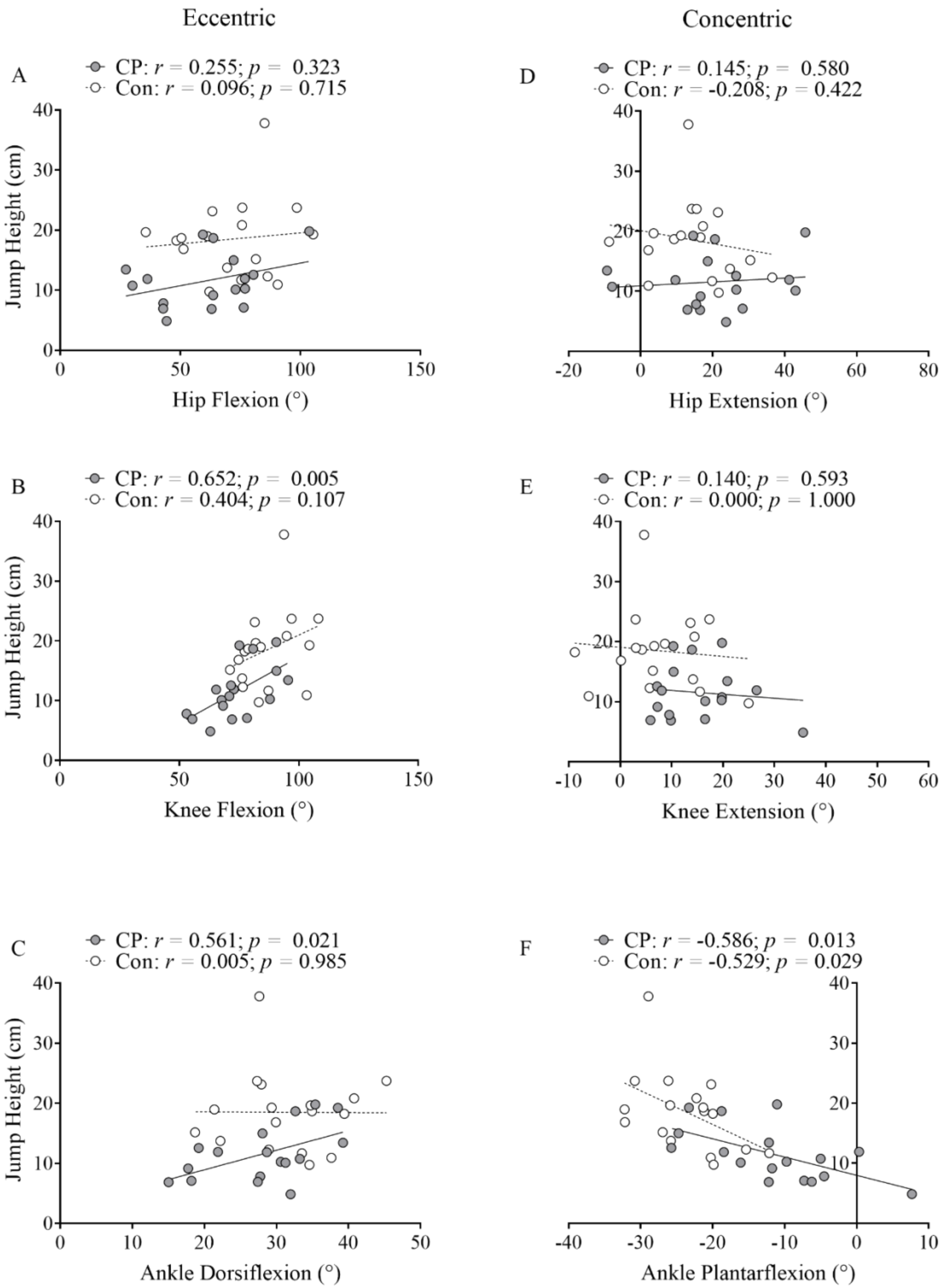
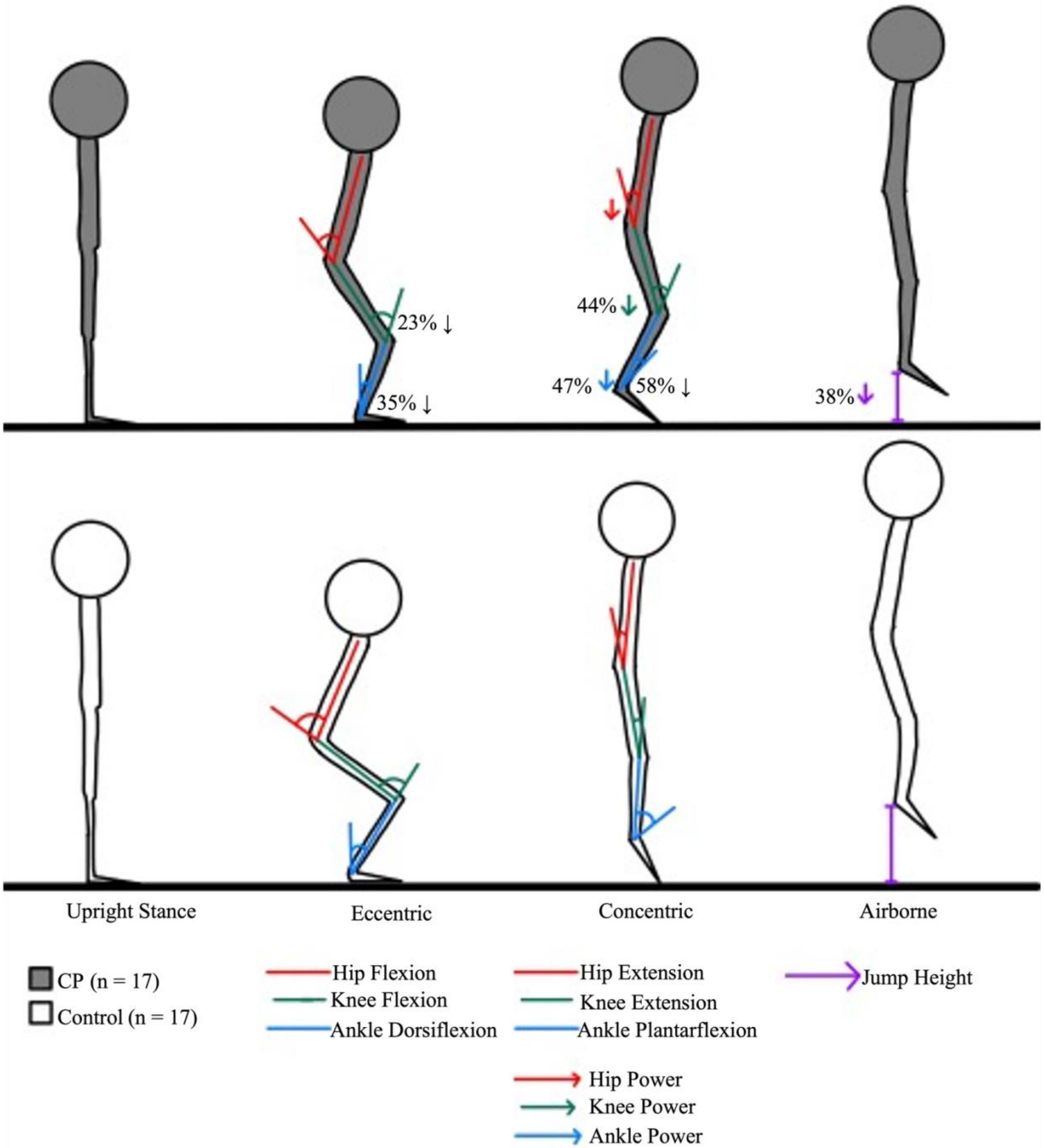

Eccentric
Concentric
A
CP: r = 0.297; p = 0.248
Con: r = 0.164; p = 0.529
Jump Height (cm)
Hip Flexion (°)
D
CP: r = 0.152; p = 0.560
Con: r = -0.125; p = 0.633
Hip Extension (°)
B
CP: r = 0.708; p = 0.001
Con: r = 0.453; p = 0.068
Jump Height (cm)
Knee Flexion (°)
E
CP: r = 0.078; p = 0.765
Con: r = 0.000; p = 1.000
Knee Extension (°)
C
CP: r = 0.201; p = 0.439
Con: r = 0.083; p = 0.751
Jump Height (cm)
Ankle Dorsiflexion (°)
F
CP: r = -0.152; p = 0.560
Con: r = -0.304; p = 0.236
Ankle Plantarflexion (°)

Figure 7.



Eccentric
Concentric
A
CP: r = 0.255; p = 0.323
Con: r = 0.096; p = 0.715
Jump Height (cm)
Hip Flexion (°)
D
CP: r = 0.145; p = 0.580
Con: r = -0.208; p = 0.422
Hip Extension (°)
B
CP: r = 0.652; p = 0.005
Con: r = 0.404; p = 0.107
Knee Flexion (°)
E
CP: r = 0.140; p = 0.593
Con: r = 0.000; p = 1.000
Knee Extension (°)
C
CP: r = 0.561; p = 0.021
Con: r = 0.005; p = 0.985
Ankle Dorsiflexion (°)
F
CP: r = -0.586; p = 0.013
Con: r = -0.529; p = 0.029
Ankle Plantarflexion (°)

Figure 8.



23% ↓
35% ↓
44%
47%
58% ↓
38%
Upright Stance
Eccentric
Concentric
Airborne
CP (n = 17)
Control (n = 17)
Hip Flexion
Knee Flexion
Ankle Dorsiflexion
Hip Extension
Knee Extension
Ankle Plantarflexion
Hip Power
Knee Power
Ankle Power
Jump Height

CHAPTER 4

CONCLUSIONS AND SUMMARY

The aim of this study was to determine if there is a deficit in jump performance in ambulatory children with CP and if the expected deficit is related to discrepancies in their lower body joint kinetics and kinematics. Jump height and lower body joint kinetics and kinematics were assessed in the MAL and LAL using a 3D motion capture system and two force platforms. Hip, knee, and ankle joint power, and maximal hip and knee flexion and extension, and maximal ankle dorsiflexion and plantarflexion in the sagittal plane were determined in each limb.

The primary observation was that children with CP have a deficit in jump performance, as indicated by their lower jump height compared to typically developing children. Specifically, jump height was almost 40 % lower in children with CP compared to controls. Further, knee and ankle power generation in the MAL were more than 40 % lower in children with CP compared to controls. The children with CP also had lower power generation in the LAL, though the magnitude of the deficit was less and limited to the ankle. In addition, children with CP exhibited lower hip, knee, and ankle ROM in the MAL and LAL during the preparatory phase of the jump cycle compared to controls, but the deficits were greater in the MAL. The low ROM in the knee and ankles was attributed to reduced knee flexion and dorsiflexion, respectively, during the eccentric subphase of the jump and reduced knee extension and plantarflexion, respectively, during the concentric subphase. As hypothesized, the lower jump height in children with CP was related to their power generation and ROM at the hip, knee and ankle. The relationships between jump height and power generation were slightly stronger on the MAL than on the LAL.

Conversely, the relationships between jump height and joint ROM were slightly stronger on the LAL.

Overall, the results are important because they suggest that jumping is compromised in children with mild CP and limited power generation and ROM in the ankles and knees may be the primary contributors. Future studies should determine if treatments that target these areas lead to improvement in jump performance in children with CP.

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