

Special Article – Cerebral Palsy

Kinematic Motion Analysis in Upper Extremity Cerebral Palsy

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Abstract

Management of physical impairment in children with upper extremity cerebral palsy is complex and multifaceted. In this patient population, clinical presentation and neurologic involvement is widely variable. Management decision making, particularly with respect to surgical and invasive interventions, is built on comprehensive history, physical examination, and assessment of function. In that cerebral palsy is a disorder of movement and posture, additional methods of assessment of the movement disorder have been developed and validated. Historically, kinematic data in the lower extremities has preceded advancements in the upper extremities due to complexity of motion and multiple body segments. In the upper extremity, motion assessment has been validated for rating videos for joint positioning and functional impairment. Kinematic data collected during functional tasks assesses deficiency. Kinematic data has involved video capture and review, electromyography, and fixed marker tracking. Sophisticated software and technological advancements are promising to aid upper extremity kinematic assessment in children with cerebral palsy. Ultimately, these technologies may play a significant role navigating complex treatment algorithms.

Keywords: Cerebral palsy; Video; Motion analysis; Kinematics; Upper extremity

Abbreviations

CP: Cerebral Palsy; EMG: Electromyography; ROM: Range of Motion; FCU: Flexor Carpi Ulnaris; PT: Pronator Teres; ECU: Extensor Carpi Ulnaris; SHUEE: Shriners Hospital for Children Upper Extremity Evaluation; ECRL: Extensor Carpi Radialis Longus; ECRB: Extensor Carpi Radialis Brevis; BR: Brachioradialis, ECRB: Extensor Carpi Radialis Brevis.

Introduction

Cerebral palsy (CP) is a disorder of development of movement and posture causing activity limitations that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain. Wide variability in the manifestation of impairment exists depending on the extent and location of the central nervous system lesion. Abnormal innervation ultimately results in imbalance of muscle forces across multiple joints, affecting different muscles and different joints to varying degrees. The most common manifestations in the upper extremity include shoulder adduction with internal rotation, elbow flexion, forearm pronation, wrist flexion and ulnar deviation, finger flexion, and thumb in palm deformities.

Patient evaluation in the upper extremity includes a careful history and physical examination. History includes a subjective patient and parent assessment of functional limitations. Physical examination includes active and passive range of motion of all joints, as well as assessment of muscle tone and control. Sensibility of the hand with assessment of stereo gnosis function helps understand functional use patterns, as the sensory cortex, as well as the motor cortex, of the brain is commonly affected. Historically, classification

of upper extremity involvement in CP has been subjectively based on examiner interpretation, functional tests, and physical examination [1-4].

In that cerebral palsy is a disorder of movement and posture, additional methods of assessment of the movement disorder are necessary. Static and dynamic assessment of limb mechanics informs therapeutic decision making [1]. Analysis of motion in the upper extremity is integral to guiding rehabilitation and management of individuals with CP. Techniques for analysis static and dynamic upper extremity mechanics can include electromyography (EMG), wearable marker kinematic measurement, and motion capture. This review investigates how motion analysis is being used for assessment of upper extremity dysfunction due to CP, as an adjunct for decision making in this complex patient population.

Upper Extremity Cerebral Palsy

Upper extremity involvement in children with CP is pervasive and is commonly assessed by the Manual Ability Classification System (MACS), which describes how children (4-18 years) with cerebral palsy use their hands to handle objects in daily activities. . Of children with CP ages 4-14, approximately 64% are independent with activities of daily living in the upper extremity (MACS I-II) and 14% are completely dependent (MACS V). Thumb-in-palm deformity was noted in 41% of children, with a predilection for those with spastic quadriplegia [3-6]. No or minimal digital flexor spasticity was reported in 69%, moderate spasticity in 23%, and no active wrist or finger extension in 2%. Typical imbalance results in elbow flexion, forearm pronation, wrist flexion, ulnar deviation, finger flexion, and thumb-in-palm deformity. There is some evidence that correction

of distal impairments in the upper extremity may improve proximal kinematics [7].

The paradigm for management of upper extremity involvement in children with CP is broad. Non-operative interventions include tone management with medications including botulinum toxin A injections; therapies including constraint-induced movement therapy, bimanual training, mirror therapy, hand therapy, Kinesio tape, or somatosensory training; as well as splinting, and electrical stimulation [8]. Surgical intervention has been shown to improve static and dynamic limb positioning as well as improvement on functional testing [4,9-13]. Guidance of surgical intervention in upper extremity procedures relies on careful examination and assessment of muscle imbalance, abnormal limb positioning, and functional impairment [9,11].

Motion Analysis

Delineation of upper extremity kinematics has evolved substantially over the last century. At one end of the spectrum is qualitative description of during routine daily activities. Kinematics of the upper extremity tasks have been assessed since the 1960's using rudimentary electrogoniometers to measure joint motion and angular velocity [14]. More recent studies have integrated video recordings, EMG, optoelectric and ultrasound tracking, and most recently 3-D pattern recognition. The use of these technologies and the findings in the literature are summarized.

Video Recordings

For many years, video recordings have been used to supplement the evaluation of upper and lower extremity kinematics. Historically, the bulk of this literature has quantified anthropomorphic norms. It has been widely used in sports and assessing repetitive workplace trauma [14]. Video recording of children, particularly in the home environment, has been used to develop several classification systems of upper extremity and hand dysfunction [15,16].

One example of goniometric data extracted from video recordings is demonstrated by Kruelen et al [17,18]. Video recording data is collected from bi-planar cameras on a global coordinate system (Figure 1). Synchronized data is collected of subjects maximally pronating and supinating forearms and lifting a class and a wooden disk at shoulder height. Angular measurements are manually calculated from isolated video frames, which are translated into angular velocity and range of motion (ROM) data. Accuracy of the model is predicted within 5 mm. Ink markings were made over bony prominences about the elbow, wrist, acromion, and sternum. In the first study, the authors examine a cohort of patients with CP and pronation and wrist flexion deformities. They had spasticity of the flexor carpi ulnaris (FCU) and pronator teres (PT) with poor active but good passive ROM. These patients were indicated for PT rerouting and FCU to extensor carpi ulnaris (ECU) transfer. Examination pre- and postoperatively demonstrates a mean supination increase of 63°, active ROM increase of 23°, and active pronation decrease 40° [17]. The second study using this technique compared 10 patients with hemiplegic CP with impaired supination of the forearm to 10 control subjects. They demonstrate increased lateral and anterior trunk bend as a compensatory mechanism for elbow flexion and pronation deformities.

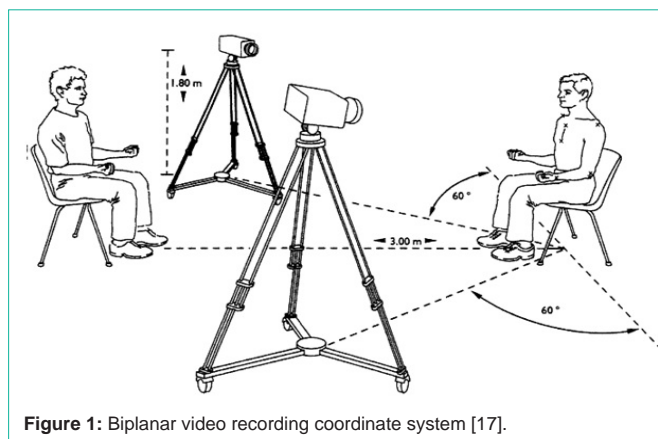


Figure 1: Biplanar video recording coordinate system [17].

Table 1: SHUEE tasks by body segment [2].

Segment Analyzed	Task	Dynamic Positional Analysis
Thumb and fingers	Pulling money from wallet Folding paper Tearing paper Stringing bead Unscrew bottle cap	Thumb – in-palm deformity, web space closed, web space open Finger – flexion, neutral, hyperextension
Wrist	Pull Play-Doh apart Cut Play-Doh with knife Throw large ball	Wrist flexion, neutral, extension, ulnar deviation, radial deviation
Forearm	Accept coins in palm Hi-five Hand to mouth Touch contralateral ear	Forearm extreme pronation, pronation, neutral, supination
Elbow	Don sock Tie shoe Place sticker on ball Crawl	Elbow extreme flexion, flexion, extension

In 1996 the Shriners Hospital for Children Upper Extremity Evaluation (SHUEE) was devised to assess upper extremity function in children with hemiplegic CP [2,19]. Standardized tasks of daily living are administered, generally by an occupational therapist. Review of the video recordings allows scoring of thumb, finger, wrist, forearm, and elbow function. A basic survey consisting of demographic information, baseline activities of daily living, independence, goals, and tone is completed first. Passive and active ROM is quantified. Three domains are subdivided by the SHUEE, including Spontaneous Functional Analysis, Dynamic Positional Analysis, and Grasp/Release Analysis. Any standard video recorder can be used in a space large enough to toss a ball and crawl. The camera is repositioned as needed to adequately visualize the desired body segment. Body segments are assessed in sequence through 16 tasks (Table 1). Spontaneous Functional Analysis scores each task based on the modified House Scale from 0 to 5 and aggregates these data. Dynamic Position Analysis is a qualitative description of ROM at each body segment. This functional tool has shown excellent inter observer reliability and correlation with other functional tests. It has demonstrated quantifiable change after surgical intervention [2,9,11,20].

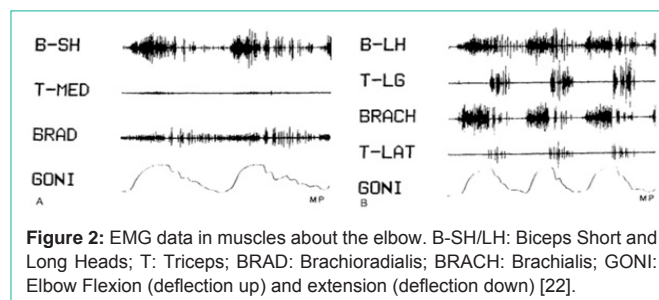
Table 2: Wrist Treatment Algorithm for Patients Undergoing Motion Laboratory Analysis [9].

Motion Laboratory Findings	Treatment Rendered
Minimal abnormalities	No wrist treatment
Phasic firing of FCU Phasic firing of ECRB/ECRL Mild wrist flexion/ulnar deviation positioning Full passive ROM of wrist	FCU Botox injection
Phasic firing of FCU Phasic firing of ECRB/ECRL Significant wrist ulnar deviation (no flexion) positioning Full passive ROM of wrist	Extensor carpi ulnaris to ECRB transfer
Phasic firing of FCU Minimal/no firing of ECRB/ECRL Significant wrist flexion/ulnar deviation positioning Full passive ROM of wrist	FCU to ECRB tendon transfer
Phasic firing of FCU Minimal/no firing of ECRB/ECRL Significant wrist flexion/ulnar deviation positioning Limited ROM of wrist	FCU to ECRB tendon transfer with proximal row carpectomy
Spastic firing of FCU Phasic of ECRB/ECRL Significant wrist flexion/ulnar deviation positioning Limited ROM of wrist	FCU lengthening or flexor pronator slide
Spastic firing of FCU Minimal/no firing of ECRB/ECRL Significant wrist flexion/ulnar deviation positioning Limited ROM of wrist	Lengthening of FCU with brachioradialis or extensor carpi ulnaris to ECRB
Minimal motor control of FCU or ECRB	

Electromyography and Video Capture

Motion capture in conjunction with EMG has been used to delineate phasic control of individual muscles. In the setup described by Van Heest et al [1,10], EMG data is collected from needle electrodes in the PT and FCU. Laboratory setup consists of bi-planar video frames while monitoring EMG data, allowing for assessment of deformity in the coronal and sagittal planes. Surface electrodes are used for the extensor carpi radialis longus (ECRL) and extensor carpi radialis brevis (ECRB). The child performs the Jebsen-Taylor functional test which involves writing, manipulating small objects, stacking, and light and heavy can lifting. EMG firing patterns are collected and simultaneously assessed during functional activity. Normal firing of the FCU produces signal during release and absence of signal during grasp. Continued firing of the FCU implies spasticity and indicates a lack of phasic control. A spastic muscle is a poor donor for tendon transfer, but may be amenable to botox injection or lengthening.

Van Heest et al [21] review 7 patients who underwent FCU to ECRB tendon transfer and PT release with pre- and postoperative video/EMG analysis. This was a group of patients selected for favorable phasic control of the FCU, facilitating transfer to the ECRB. Postoperative findings demonstrated phase change in 1 patient. Postoperatively, 4 patients were able to place a can on a shelf, compared to only 2 preoperatively. The majority pattern was firing of the FCU during release, though now acting as a wrist extensor, and thus not synergistic with finger flexion. A broader study using the same motion lab was performed on 48 patients with hemiplegic CP undergoing surgery for wrist deformity [9]. Surgical decision making based on examination and motion lab findings is outlined in Table 2. Results showed improvement of finger, wrist, elbow, and forearm positioning during functional tasks based on the SHUEE Dynamic Positional Analysis.



EMG findings have been assessed in the upper extremity after traumatic brain injury or stroke [22,23]. Video and goniometric data are collected simultaneously. Out-of-phase and continuous firing of the brachioradialis (BR) is noted, as well as prolonged firing of the biceps with elbow extension (Figure 2). Similar patterns are noted across the wrist; however there is significantly more variability in the presentation. Hoffer et al [24] review 23 patients who underwent EMG analysis for patient with CP presenting with a thumb-in-palm deformity. EMG of the adductor pollicis informed surgical decision making regarding total or partial muscle release. EMG has been used successfully to facilitate treatment, though it is limited in the wide variability of presentation, cost, and invasiveness.

Marker Tracking

Wearable markers are subject to interference with adjacent anatomic segments. Wearable devices add weight and alter soft tissue tension, which can alter kinematics [11,25,26]. Prior attempts to capture hand kinematic data in children with CP have been limited by these constraints [1]. Modeling of the hand has typically involved a single marker or a glove with transducers (Figure 3). This methodology has been the gold standard of upper and lower extremity kinematic analysis over the last 2 decades.

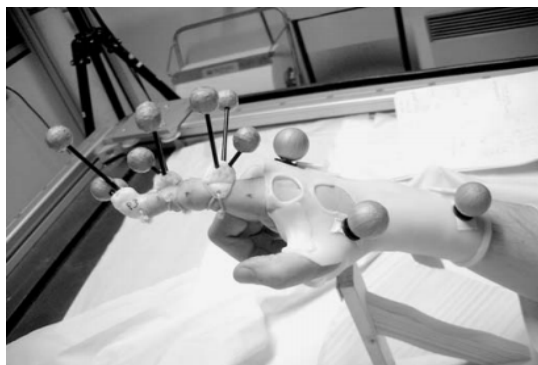


Figure 3: Glove optoelectric sensor allowing for capture of index finger motion segments [26].

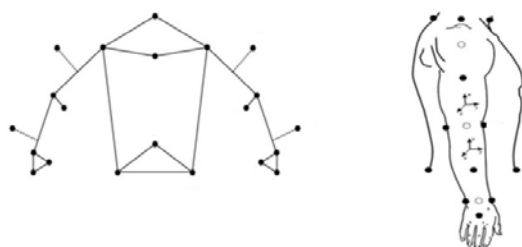


Figure 4: Upper extremity modeling of body segments with optoelectric markers [27].

Mackey et al [27] examined 10 normal children compared to 10 children with a diagnosis of hemiplegic CP. Optoelectric markers were fixed on bilateral upper limbs and trunk, with a single marker used for the shoulder and a single marker for the hand (Figure 4). The model combined shoulder with scapulothoracic motion and estimated joint by anthropomorphic data. A hand-to-head task, hand-to-mouth task, and reach task were evaluated. Children with hemiplegia demonstrated decreased elbow extension and supination with compensatory trunk flexion in grasping techniques. Additionally, they demonstrated slower peak angular velocities and longer completion times compared to the non-dominant arm in control subjects. Bimanual dexterity in children with hemiplegic CP tended to exacerbate deficiencies in the affected hand when the dominant arm took over. Similar protocols have been described, demonstrating longer duration for task completion with decreased smoothness of trajectory [28-31].

Fitoussi et al [7] describe a similar protocol in patients with spastic cerebral palsy. Of their patient population, 4 underwent botox injection and 4 underwent surgical lengthening procedures. Children with hemiplegia demonstrated relative shoulder abduction and external rotation, elbow flexion, forearm pronation, wrist ulnar deviation, and lateral trunk bending. After PT, FPL, or adductor polices lengthening, patients had decreased shoulder and trunk compensatory motion. This reinforces the theme of proximal compensation for distal dysfunction, and highlights the importance of collecting sound kinematic data in the more challenging distal body segments.

3-D Motion Capture

Recently time-of-flight cameras have gained significant traction in

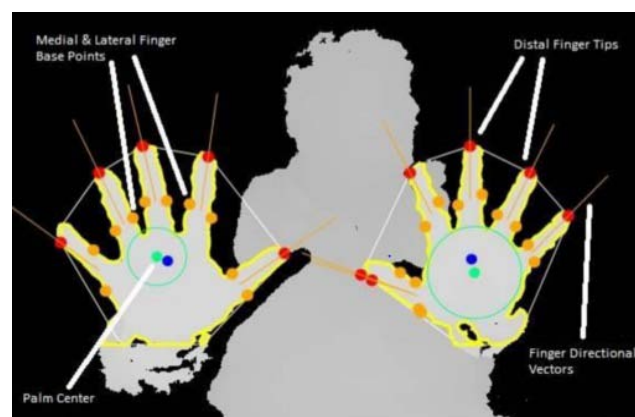


Figure 5: Motion capture technology.

commercial use. These devices measure the time taken for a projected light signal to reflect off an object. The depth and 3-D structure of the object is mapped. This allows very rapid image capture, though it can be limited by resolution, interference, and background lighting. These commercial models have built-in algorithms for modeling the hand. These biomechanical equations allow for the creation of the 3-D representation of dynamic finger, thumb, wrist, and forearm movement. These devices contain traditional visible light capture cameras which can digitally mined post hoc. The cost for off-the-shelf 3-D cameras is around \$150. One such device, the Xbox Kinect™, has gotten significant attention in the last 5 years. Clinical applications have explored involved diagnostic evaluation of autism, CMC arthritis, Parkinson's disease, sports, stroke, and CP. Significant research is devoted to the use of 3-D motion capture (Figure 5) in rehabilitation, therapy, and biofeedback.

Many studies have investigated the precision and accuracy of the system compared to gold-standard optoelectric marker tracking. Kuster et al [32] examined 20 normal subjects with both optoelectric markers and a Kinect™ system and found accuracy within $3.9 \pm 4.0^\circ$ for shoulder motion and $0.1 \pm 3.8^\circ$ for trunk motion. Accuracy of the system appeared to dip when body segments overlapped in the view of the Kinect™.

Rammer et al [33] published a pilot study of an algorithm developed to quantify upper extremity kinematics during activities of daily living using the Kinect™. They examined 12 normal pediatric subjects administering a SHUEE examination and collecting depth and video data during functional tasks. All subjects had 100% scores on the SHUEE examination. Absolute kinematic data were collected, though variable between the subjects. The examiners were able to extract patterns of motion which seemed to correlate with specific tasks. For example, unscrewing a bottle correlated strongly with wrist ROM, peak wrist velocity, and peak wrist acceleration. It correlated with elbow and shoulder ROM secondarily. These models may ultimately provide normalized kinematic data, and perhaps more importantly, they may illustrate typical patterns of compensation. In the future, this may provide valuable information about compensatory deficiencies in the CP population.

Discussion

Compared to lower extremity kinematics, there are significant

challenges to upper extremity analysis. The lower extremities can be simplified to a few anatomic segments and degrees of freedom with closed-chain, weight-bearing force analysis. Upper extremity analysis, on the other hand, involves a much higher number of anatomic segments, each with several degrees of freedom. Additionally, force transduction in the upper extremity is unconstrained and much more difficult to quantify in functional tests. In the upper extremity, there is variability between normal subjects in functional kinematics used to complete a task. There is substantial redundancy in the upper extremities, not found in the lower extremities, which confounds analysis [14]. This redundancy and normal tendency toward compensation suggests that absolute measurements of ROM and angular velocities may be limited in correlation with function, except at extremes. Rather, pattern recognition and categorization of dynamic motion may provide more fruitful in differentiating pathology, and more importantly may inform how individuals may best respond to treatment. Finally, it is speculated that central nervous system plasticity without neurologic impairment allows functional adaptation and compensation [34].

Assessment of dynamic motion is crucial to management of upper extremity involvement in children with CP. This technology is rapidly blossoming in the commercial sector. Advancements of these technologies can evolve into robust clinical decision making for children with upper extremity CP. Standardization of indications for invasive interventions are clearly needed. There is wide variability in clinical manifestations of upper extremity CP as well as non-surgical interventions and operative techniques. Functional assessment tools and current classification schemes can elucidate the quality and magnitude of impairment, but are presently too blunt to guide management [15]. EMG has been used successfully to probe dynamic muscle use, but is limited by expense and invasiveness. Optoelectric markers have been employed successfully in the evaluation of lower extremity CP, but are prone to interference with functional use during the assessment in the upper extremity. This is especially challenging in the hand.

Motion capture technology shows potential as a non-invasive, low-cost, reproducible alternative. Sophisticated video analysis and time-of-flight data may allow classification of dynamic patterns within functional upper extremity limb use. Ultimately, outcomes of surgical and non-surgical interventions may be weighed against the automated motion capture, leading to finely-tuned management indications.

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