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DEVELOPMENT AND RELIABILITY OF AN INSTRUMENTED ASSESSMENT PROTOCOL FOR UPPER LIMB MOVEMENTS IN DYSKINETIC CEREBRAL PALSY

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Abstract

Lackness of objective measurements in the upper limb movement impairments makes it more difficult for therapy evaluation and rehabilitation to manage the dyskinetic cerebral palsy (DCP). Uncontrollable movements and unpredictability that reflect choreoathetosis and dystonia are not fully described and explained by clinical rating scales. To develop and evaluate an Instrumented Dystonia and Choreoathetosis Assessment (IDCA) procedure that analyzes upper limb movement in children and young people with DCP by combining three-dimensional optometric motion capture with inertial measurement units (IMUs). Three functional upper limb tasks, such as reach-to-grasp vertically, reaching forward, and reaching sideways, are responsible for making up the IDCA protocol. A multi-camera optometric system was used to chart the upper limb kinematics. Synchronized IMUs were used to record acceleration and segmental angular velocity. The coefficient of multiple correlation (CMC) was employed to assess the consistency of acceleration, joint kinematics, and angular velocity waveforms across and between all sessions. Optometric equipment demonstrated good to exceptional reliability within and between sessions for upper limb joints. IMU-derived angular velocity demonstrated greater consistency and provided moderate to good reliability compared with acceleration-based measurements. It has been observed that reliability was usually higher within sessions than between sessions. The IDCA protocol provides a comprehensive, practical, and trustworthy objective measurement of upper limb movement characteristics in DCP patients. It provides a potential opportunity for intervention monitoring and clinical evaluation supported by complementary data from IMUs and optometric motion capture.

INTRODUCTION

Cerebral palsy is a brain abnormality that develops in the fetus or infant and affects posture and movement development. It is non-progressive in nature (Haberfehlner et al., 2020). Dyskinetic cerebral palsy is a clinical subtype of CP. It has two clinical subtypes, marked by erratic, involuntary movements, choreoathetosis, and dystonia. These clinical subtypes significantly impair the voluntary movements (Ralph, Carroll, Danks, & Harvey, 2023). Functional upper limb tasks are very challenging and unpredictable for people with DCP since these movement abnormalities often get worse with deliberate efforts (Burç, Özal, & Günel, 2025). Upper limb impairment significantly affects daily activity, engagement, and independence in DCP. Two examples of observational rating scales that are commonly used in clinical examination of dystonia and dyskinesia are the Burke-Fahn-Marsden Dystonia Rating Scale and the Barry-Albright Dystonia Scale (Burke et al., 1985) (Barry, VanSwearingen, & Albright, 1999). These instruments are limited by subjectivity, ceiling effects, and diminished sensitivity to minute fluctuations in movement quality and variability, especially during difficult functional tasks, despite their extensive usage in clinical practice (Barry et al., 1999).

Instrumented motion analysis helps provide an objective alternative by quantitatively assessing movement patterns and joint kinematics during task execution. Three-dimensional optometric motion capture devices can facilitate objective measurement of upper-limb movement patterns among children with CP and other neurological conditions (Rozaire et al., 2024). These approaches facilitate the investigation of comprehensive inter-joint coordination, movement variability, and joint angles, which are usually critical to assess in dyskinetic movement disorders. But its practical application is generally hindered due to the high cost of laboratory equipment and its limited accessibility (Vanmechelen et al., 2022). A recent advancement in wearable sensor technology, especially in inertial measurement units (IMUs), has made it feasible to monitor all movement dynamics in daily life and in clinical settings. This method is cost-effective and portable, which makes its practical application more feasible (Vanmechelen et al., 2023). By providing crucial information on angular velocity and movement smoothness, IMUs can improve optometric kinematic data. There is presently limited data available to assess the therapeutic usefulness and validity of IMU-based assessment for patients with dyskinetic cerebral palsy in upper-limb movements despite its rising use in neurological conditions (Rose-Dulcina, Armand, & Cacioppo, 2025).

There are certain gaps left in the evaluation of Dyskinetic cerebral palsy, in-spite of the increasing use of instrumented motion analysis. Most of the research focuses on spastic or hemiplegic subtypes and the clinical importance of instrumented upper limb assessments in Dyskinetic cerebral palsy, which is characterized by significant movement variability, is not fully evaluated. Additionally, wearable inertial sensors and optometric motion capture are rarely assessed jointly in a single standardized methodology, which restricts direct comparison of their dependability and capacity to describe functional task performance. As a result, there is a dearth of comprehensive data relating measurement reliability to clinically significant movement characteristics during upper limb activities, such as variability, task duration, and joint configuration. The goal of the current study was to create an Instrumented Dystonia and Choreoathetosis Assessment (IDCA) procedure that integrates IMUs with optometric motion capture, and to assess the reproducibility of this protocol both within and between sessions in children and young adults with DCP. We predicted that angular velocity measurements would be more reliable than acceleration-based measurements and that the IDCA (Inertial Device–based Clinical evaluation) procedure would show respectable reliability for upper limb kinematic evaluation.

2. Methods

2.1 Participants

Specialized education and rehabilitation facilities were used to find participants with DCP. Manual Ability Classification System (MACS) levels I–III, age between 5 and 25 years, and a clinical diagnosis of DCP were the requirements for inclusion. Recent botulinum toxin injections, orthopedic or neurosurgical procedures performed within the previous year, or other neurological conditions were among the exclusion criteria. In order to compare reliability, typically developing (TD) participants were enlisted as a reference group. The institutional review board gave its ethical approval, and written informed consent was acquired.

2.2 Development of the IDCA Protocol

In order to capture clinically significant upper limb movement features, the IDCA procedure was created after a review of the literature and expert consultation. Reaching forward, reaching sideways, and reach-to-grasp vertically were the three functional tasks chosen. These tasks were chosen to elicit multi-joint coordination, distal control, and movement variability commonly affected in DCP.

2.3 Instrumentation

A multi-camera optometric motion capture system sampling at 100 Hz was used to record upper limb kinematics. In accordance with established anatomical criteria, reflective markers were applied to the trunk, scapula, upper arm, forearm, and hand. To record triaxial angular velocity and acceleration at 100 Hz, five synchronized IMUs were installed on matching segments.

2.4 Experimental Procedure

Participants were seated in a regular position and completed each task at their own pace. Three trials each session, with 10 repetitions of each task per trial. On the same day, two measurement sessions were carried out to evaluate dependability both within and between sessions. Both static and dynamic calibration processes were carried out before the task was carried out.

2.5 Data Processing

From the point of task accomplishment to the point of hand contact at the ipsilateral knee, movement cycles were divided. In order to reduce sensor orientation effects, joint angles were computed using optometric data, and angular velocity and acceleration norms were obtained from IMU data. Before analysis, the waveforms were time-normalized.

2.6 Statistical Analysis

To process the kinematic sensor and inertial data offline, custom scripts were used. Beginning and termination points of all the trial's movements were effectively noted. This data was divided into parts. One is for the movement initiation, and the other is for the point of task attainment (PTA). Time normalization of each waveform to 100% of the movement cycle facilitates the comparison between the subjects and trials. The coefficient of multiple correlation (CMC) was determined for the joint angle waveforms. It is obtained from angular velocity waveforms and optometric motion capture, which are derived from IMUS. It was used to assess and check the reliability of waveforms (Kadaba et al., 1989). Reliability was further assessed across testing sessions (across testing sessions) and within the same session (repeated trials within the same sessions). The interpretation of CMC values was as follows: bad (<0.65), moderate (0.65–0.75), good (0.75–0.85), or excellent (>0.85).

CMC values were used to measure movement variability over repeated trials for each task. The time from movement initiation to PTA was used to calculate task duration. To describe movement methods, joint angles at PTA were extracted for the wrist, elbow, and shoulder. Group differences between people with dyskinetic cerebral palsy (DCP) and normally developing participants were summarized using descriptive statistics.

3. Results

3.1 Optometric System Reliability

The optometric system demonstrated predominantly good to excellent within-session reliability across upper limb joints. Lower reliability values were observed for trunk movements, particularly during tasks involving minimal trunk displacement.

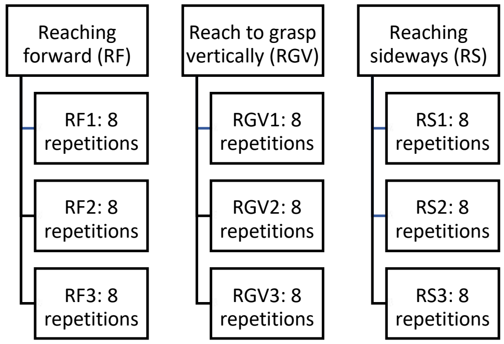

Figure 1. Example of joint angle waveforms and mean waveform for elbow flexion–extension during reaching forward.

Between-session reliability remained moderate to excellent for most joints, with reduced consistency observed in wrist deviation measures.

3.2 IMU Reliability – Angular Velocity

IMU-derived angular velocity waveforms showed good to excellent within-session reliability, particularly at the upper arm and wrist. Between-session reliability was generally lower but remained acceptable for proximal segments.

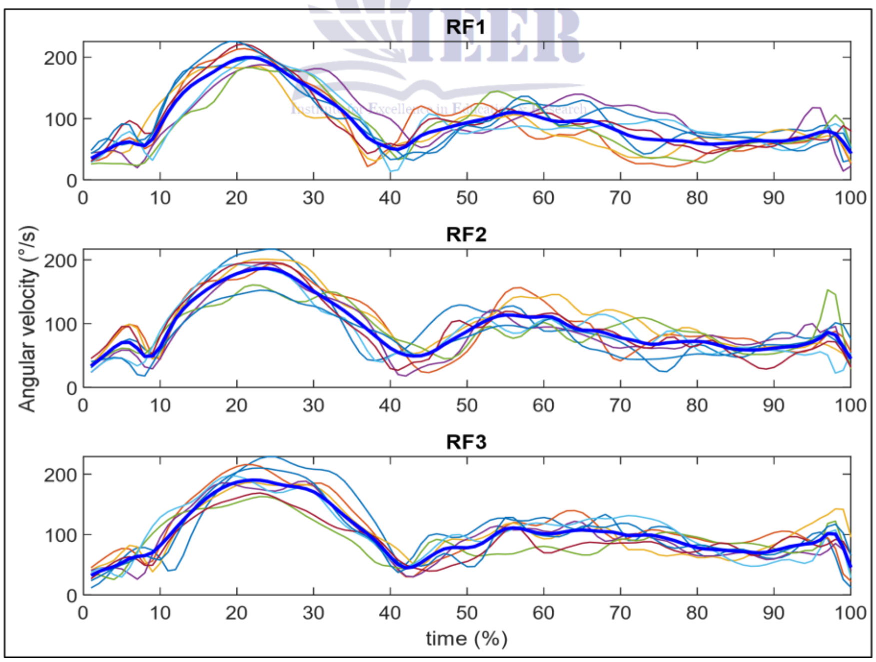

Figure 2. Mean angular velocity waveforms (±SD) recorded at the upper arm during reach-to-grasp.

It illustrates time-normalized upper limb joint angle waveforms across repeated trials for participants with dyskinetic cerebral palsy and typically developing controls during functional

reaching tasks. Joint angle trajectories suggest consistent, reliable movement patterns among participants who are developing a high level of overlap between repetitions. In comparison, participants with dyskinetic cerebral palsy exhibit a significant dispersion in the joint angle waveform across the repeats. It indicated the presence of a greater degree of intra-individual movement variability. Trial-to-trial variations are noticeably observed even under the same task conditions at the elbow and wrist joints. Consistency with the observed waveform dispersion is demonstrated by low coefficient of multiple correlation (CMC) values from the reliability analysis. These low results show that involuntary, changing muscular activity has a major impact on a dyskinetic cerebral palsy patient's ability to accomplish movements.
This movement inconsistency is a definitive feature of the dyskinetic upper motor control. Figure 2, presented above, provides strong support for the quantitative result findings.

3.3 IMU Reliability – Acceleration

The comparison between sessions indicated that acceleration-based measurements were less significant and less reliable than angular velocity. Distal segments showed a high degree of dependency on the greater motion ranges.

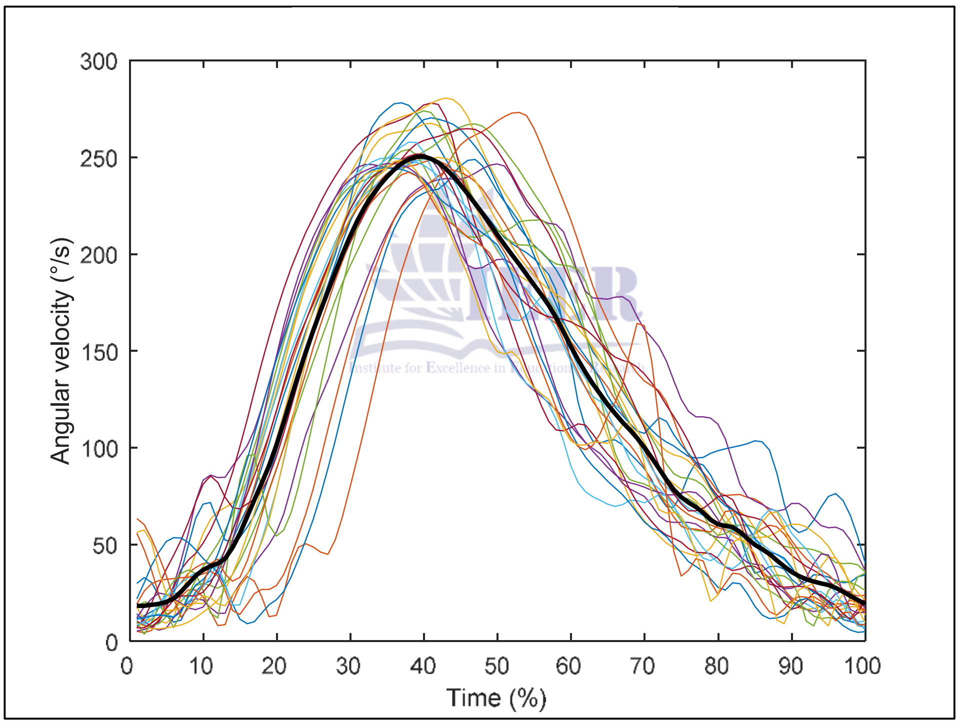

Figure 3. Comparison of CMC values for acceleration and angular velocity across the upper limb

Joint angles for the shoulder, elbow, and wrist while performing functional upper limb tasks at the point of task achievement (PTA) are shown in Figure 3. It shows a comparison between normally-developing control and participants with dyskinetic cerebral palsy. Participants in development typically used consistent and biomechanically effective joint configurations to accomplish task goals. On the other hand, people with dyskinetic cerebral palsy showed different joint positions during PTA, including greater wrist deviation, increased elbow flexion, and task-dependent changes in shoulder placement. These changed joint configurations show that compensatory movement techniques are used to achieve functional objectives. Participants with dyskinetic cerebral palsy depended on atypical joint positions to complete tasks successfully, indicating decreased movement efficiency and impaired inter-joint coordination. Figure 3 stresses the significance of joint-level analysis for comprehending motor dysfunction beyond observable task outcomes and shows that functional success in dyskinetic cerebral palsy does not correspond to normal movement execution.

4. Discussion

In addition to describing movement characteristics during functional tasks in people with dyskinetic cerebral palsy, this study assessed the validity of an instrumented upper limb assessment methodology. The results suggest that whereas IMU-derived angular velocity estimates exhibit moderate to good reliability, especially for proximal segments, optometric motion capture offers good to outstanding reliability for the majority of upper limb joint kinematics. These findings demonstrate that instrumented assessment is feasible in a population with substantial movement variability (Jaspers et al., 2011). Because dyskinetic cerebral palsy is characterized by involuntary and variable movements linked to dystonia and choreoathetosis, the dependability values found in this study were generally lower than those reported for spastic or hemiplegic cerebral palsy (Monbaliu et al., 2012). Instead of drawing conclusions from other CP subtypes, these results strongly emphasize the need to evaluate and measure characteristics exclusive to individuals with dyskinetic cerebral palsy. Combining IMU-based and optometric measurements provides a great opportunity for both clinically feasible movement dynamics assessment and in-depth joint-level analysis (Kleiner et al., 2018).

Participants who exhibited more movement variability, varied joint configuration, and longer task length at the time of task achievement were consistent with the hallmark of dystonia as compared to those with dyskinetic cerebral palsy. The link between voluntary motor execution and movement efficiency is disturbed by involuntary muscle activation (Burke et al., 1985). Participants with dyskinetic cerebral palsy showed increased variability during difficult distal control tasks, further validating the task-dependent characteristics of upper-limb impairment. (Barcala et al., 2019). According to recent research, an integrated instrumented approach yields more reliable and clinically meaningful data on upper motor control in dyskinetic cerebral palsy. In both research and clinical settings, monitoring the effects of interventions on dyskinetic and dystonia patients by objective assessment of movement variability and task performance may assist in enhancing the outcomes (Matthews, 2025).

5. Conclusion

For the objective assessment of upper-limb movement patterns in dyskinetic cerebral palsy, the IDCA protocol offers a thorough, reliable, and useful approach. Future clinical evaluations and intervention-monitoring procedures are made easier by the integrated observations of movement patterns and joint kinematics made possible by the combination of IMUs and optometric motion capture.

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