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Exploring Positional Performance and Force Control in a Bimanual Lifting Task Among Children with Neurodevelopmental Disabilities: A Cross-Sectional Study

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Abstract: Children with neurodevelopmental disabilities often struggle with motor control and stability, impacting their ability to perform functional tasks such as lifting and carrying objects. This study explores positional performance during bimanual box-lifting tasks in children aged 9–18 years with neurodevelopmental disabilities. A total of 83 participants, including 62 with unilateral spastic cerebral palsy and 21 with non-unilateral spastic cerebral palsy, performed tasks using the Activity of Daily Living Testing and Training Device. Tasks were conducted at maximal (80–100% force) and submaximal (40–80% force) levels of force control, with positional performance measured in six directions using Inertial Measurement Unit sensors. Statistical analyses included the Wilcoxon signed-rank test for levels of force control comparisons, Kruskal–Wallis tests for group differences, and Spearman correlations to assess relationships between maximal and submaximal performance. The results revealed that four of six positional parameters were worse in the maximal zone than in the submaximal zone ($p < 0.05$), highlighting the challenges of higher force demands. Additionally, positive correlations between maximal and submaximal performance suggest consistency across levels of force control. Maximal levels of force control increased variability, with submaximal performance proven to be a reliable predictor of maximal capabilities. This finding offers a safer and more efficient method for assessing motor performance. Overall, these results underscore the importance of targeted rehabilitation strategies focused on improving stability and precision in children with neurodevelopmental disabilities so they can perform daily tasks more independently.

Keywords: cerebral palsy; technology; positional performance; rehabilitation; upper limbs; activity of daily living

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1. Introduction

Children with neurodevelopmental disorders such as cerebral palsy (CP) and spina bifida, among other neurodevelopmental disorders, exhibit sensorimotor impairment on one or both sides of their body. These conditions can lead to challenges in motor control, affecting the ability to perform functional activities of daily living (ADLs) [1]. Cerebral palsy, including unilateral, bilateral, and dyskinetic types, is characterized by abnormal muscle tone and movement stemming from disruptions in early brain development [2]. Similarly, CP and spina bifida lead to mobility and sensory deficits. While spina bifida affects both mobility and sensory function, leading to fine and gross motor deficits, typical upper extremity problems in children include muscle weakness, impaired coordination, and reduced fine motor control. These conditions pose unique challenges in tasks that require varied levels of strength, precision, and motor control [3–5].

Despite extensive research on motor impairments in CP and spina bifida, there is limited knowledge about how these impairments affect positional stability during force-dependent tasks, such as lifting objects. Positional performance is critical for stability and precision, and its deficits may contribute to increased difficulty in handling objects and performing coordinated movements [6].

These impairments present notable challenges to motor function, especially for tasks involving upper limb functionality, which are essential for daily independence. ADLs require various levels of muscle force depending on the task. These force levels are categorized along a 0–100% scale of maximum voluntary contraction (MVC): very low (0–20%), low (20–40%), medium (40–60%), high (60–80%), and very high (80–100%) [7]. For example, fine motor tasks like eating and dressing typically require lower MVC levels, while lifting objects demands higher MVC levels. Research shows that motor unit control strategies adapt to these force demands. Small motor units are recruited during low-force, high-precision activities, while large motor units are activated for high-force tasks [8,9].

For children with neurodevelopmental disabilities, tasks that typically require low or medium MVC levels, like eating, dressing, or typing, can be especially difficult due to muscle weakness, impaired coordination, and reduced fine motor control. As task intensity increases (e.g., lifting a box), fast-twitch muscle fibers are recruited, leading to increased fatigue and reduced precision, especially for those with compromised motor units [10]. Thus, low-intensity precision and high-intensity strength tasks can be challenging, limiting their independence in ADLs.

Effective bimanual motor control is, however, critical for ADLs, especially in tasks like lifting a box or zippering a jacket that require the coordinated use of both hands [11] and bimanual dexterity [12]. Such coordination is vital for enhancing independence and improving quality of life [13]. In tasks involving object positioning (e.g., manipulating a knife, fork, or box), adequate strength enables precise, coordinated movements [14]. Optimal object positioning is essential for task execution [15]. When lifting a box, for example, its position relative to the lifter, height from the ground, and orientation affect stability and control strategies [16].

While various methods exist for assessing motor performance, Inertial Measurement Units (IMUs) offer an effective tool for capturing positional stability in different movement planes. Prior studies have demonstrated the use of IMUs in motor assessments for individuals with CP and other neuromuscular conditions, providing a reliable way to evaluate dynamic movement patterns [17–19].

This study evaluates positional performance in children with neurodevelopmental disabilities using IMUs to measure tilt angles during a bimanual box-lifting task. Stable positional performances are crucial to prevent spillage or dropping, yet how these challenges vary with force levels remains unclear. By analyzing high (80–100% MVC) and moderate-to-high (40–80% MVC) levels of force control, this study examines the impact of task difficulty on positional performance. The primary goal of the study is to focus on how different levels of force control (Max vs. SubMax zones) affect positional performance. Secondly, we want to explore whether children with different neurodevelopmental disabilities show differences in positioning performance during a bimanual box-lifting task.

Additionally, we want to examine consistency in positional performance across different levels of force control (Max and SubMax zones).

Based on these goals, we developed three hypotheses together with a hypothetical scenario where the box is filled with water. We calculate the characteristics of the box and determine the water level at which spillage is likely to occur, providing a clear and easy-to-understand representation of the situation.

1.1. Primary Hypothesis: Levels of Force Control Differences in Positional Performance and Spillage

- Null Hypothesis (H_0): Positional performance in the Max zone will be equal to or better than in the SubMax zone for at least four out of the six positional parameters, and water spillage rates will not differ significantly between the two zones.
- Alternative Hypothesis (H_a): Position performance at levels of force control within the Max zone will be worse than in the SubMax zone for at least four of the six positional parameters, and water spillage rates will be higher in the Max zone than in the SubMax zone.

1.2. Group Differences in Positional Performance and Spillage Rates

- Null Hypothesis (H_0): The positional performance of the USCP group will be equal to or better than that of the Non-USCP group in both the Max and SubMax zones, and water spillage rates will not differ significantly between these groups.
- Alternative Hypothesis (H_a): The positional performance of the USCP group will be significantly worse than that of the Non-USCP group in both the Max and SubMax zones, with higher water spillage rates in the USCP group.

1.3. Tertiary Hypothesis: Correlation Between Max and SubMax Zones

- Null Hypothesis (H_0): There is no significant correlation between the six positional parameters measured in the Max and SubMax zones.
- Alternative Hypothesis (H_a): There is a significant positive correlation between the six positional parameters measured in the Max and SubMax zones.

2. Materials and Methods

2.1. Study Design

This study employs a cross-sectional observational design to investigate positional performance and water spillage outcomes during a bimanual box-lifting task in children and adolescents with various neurodevelopmental disabilities, including unilateral spastic cerebral palsy (USCP), bilateral CP, dyskinetic CP, spina bifida, and other syndromes. The study integrates different levels of force control (Max vs. SubMax zones), group differences (USCP vs. Non-USCP), and water spillage thresholds to evaluate upper limb function in a real-world lifting simulation.

2.2. Participants

A total of 83 participants were recruited from various rehabilitation centers in the Netherlands, with all 83 completing the study. The final sample included age distribution, number of participants per disability group, gender distribution, and affected side/non-dominant side distribution, as well as classifications based on the Manual Ability Classification System (MACS) [20] and the Gross Motor Function Classification System (GMFCS) [21].

Inclusion criteria:

- Children and adolescents aged 9 to 18 years, diagnosed with a motor disability (e.g., USCP, bilateral CP, dyskinetic CP, spina bifida).
- Able to stand, sit in wheelchair, or participate with adaptive support (e.g., assistive devices, seated alternatives, caregiver assistance) to ensure equitable inclusion in assessments.
- Capable of following instructions from the research team.

Exclusion criteria:

- Any botulinum toxin injections or upper limb surgery within the past six months.

Informed consent is obtained from a parent or legal guardian, and participants aged 12 years or older also provide written assent. The study was approved by the Medical Ethics Committee of Maastricht University with Protocol ID: NL201803499/ 20110. In addition, these are regular tests in a clinical program, and informed consent letters have been signed to use the outcomes anonymously.

2.3. Material

The ADL-TTD (Activity of Daily Living Testing and Training Device) is a multifunctional device developed by UMACO B.V. in Groningen in collaboration with the University of Maastricht and the Adelante Rehabilitation Center, with funding from the Johanna Kinderfonds and Health Holland. This device features a motor, an IMU sensor (Adafruit BNO055 Absolute Orientation Sensor, Adafruit Industries, New York, NY, USA), a horizontal desktop, and various attachable objects such as a plate, a box (for bimanual tasks), or a cup (for unimanual tasks). The components are shown in Figure 1. The objects are connected to the device via a cable. The motor functions similarly to an ergometer, rolling out and locking the metal cable at a specific height when an object is pulled, thereby enabling the measurement of the object's isometric force.

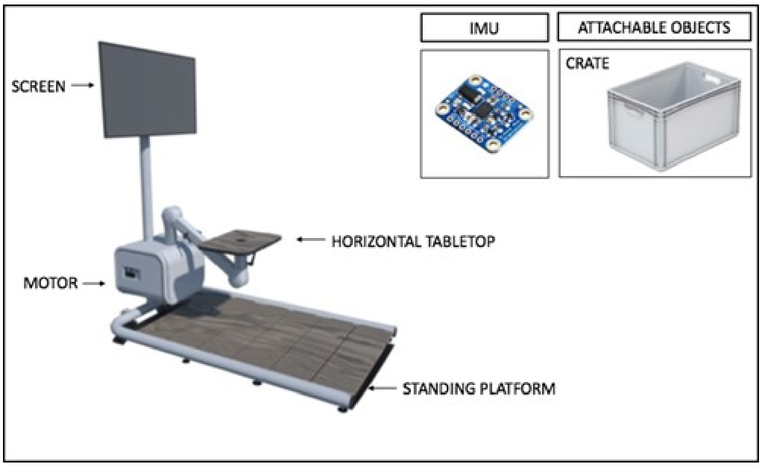

Figure 1. The parts of an ADL-TTD.

The IMU sensor is mounted at the center of each object. This sensor incorporates three types of sensors, an accelerometer, a gyroscope, and a magnetometer, allowing it to precisely measure acceleration, angular velocity, and magnetic field by integrating the data from these sensors. The ADL-TTD employs the IMUs to track the movement of the associated object, which is measured in degrees (°) of tilt along the x-, y-, and z axes. The object position can be illustrated using six directions. Figure 2 illustrates the deviation from the x-, y-, and z axes for the box. The ADL-TTD is connected to a laptop running the ADL-TTD analyzer V1.1 software, which displays the position in degrees, the height of the object from the tabletop, and the maximum isometric force. Detailed specifications for the ADL-TTD and the Adafruit BNO055 Absolute Orientation Sensor are given in Appendices Tables A1 and A2.

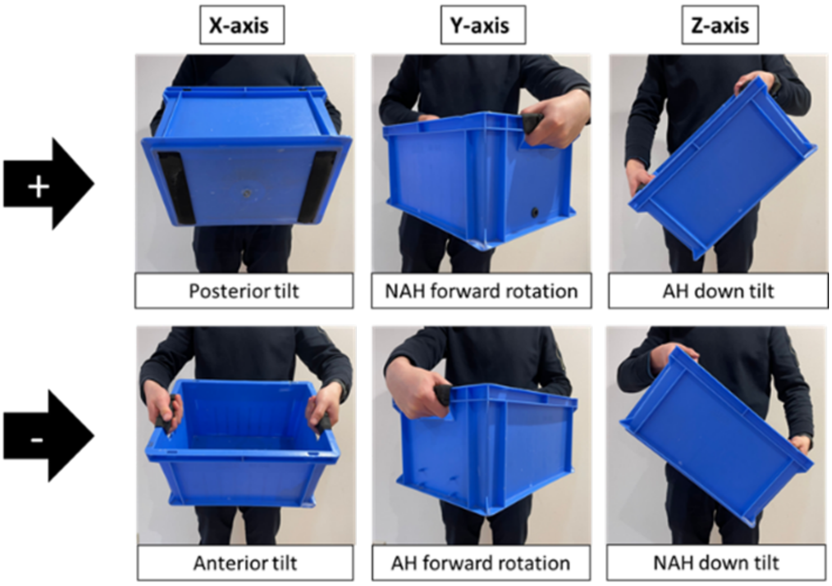

Figure 2. Six directions of tilt across the x-, y-, and z axes for the box. (In this figure, the right hand is the AH.)

2.4. Procedure

The ADL-TTD measurement procedure includes several steps to ensure accurate calibration and setup. Each participant stands or sits in front of the device, depending on their ability to stand. A box, attached to a cable, is placed on a horizontal tabletop at the participant's pelvic level (as shown in Figure 3). The device is then recalibrated in this position. A screen in front of the ADL-TTD displays the measurement sequence.

The test begins with a five-second preparation phase, during which the participant lifts the box to a height of 15 cm above the tabletop, with the rope limiting any further lift. In the following five seconds, the participant performs a maximum voluntary contraction (MVC), lifting the box as forcefully as possible while keeping it upright. This is followed by a 10-second recovery period, allowing the box to be returned to the tabletop. The process is repeated two more times.

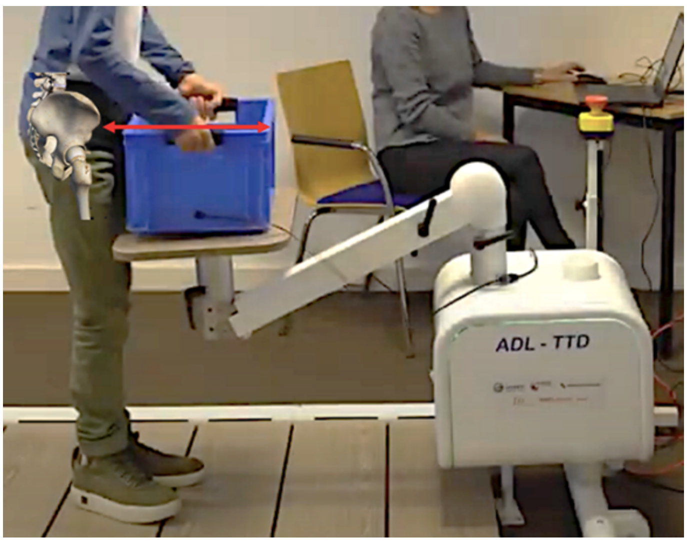

Figure 3. Measurement position when using ADL-TTD.

Participants perform a bimanual lifting task using a box attached to the ADL-TTD. The task is divided into two performance zones:

- Max Zone: Lifting tasks are performed at an intensity level above 80% of the MVC. This zone evaluates upper limb strength and positional performance during levels of force control tasks.
- SubMax Zone: Lifting tasks are performed at an intensity level of force control below 80% of MVC. This zone assesses positional performance during moderate levels of force control tasks, which are closer to real-world daily living activities.

During these tasks, IMU sensors attached to the box measure six position parameters: anterior and posterior tilt, affected hand (AH)/non-affected hand (NAH) forward rotation, and AH/NAH downward tilt. In this study, we assess positional performance using IMUs, detected along x-, y-, and z-axes in degrees°. Positional performance is evaluate at various levels of force control (very low to very high MVC) to understand how children with neurodevelopmental disabilities manage object positioning in a bimanual box-lifting task.

2.5. Primary and Secondary Variables

The primary variables focus on positional performance at maximal and submaximal levels of force control, analyzed through six positional parameters (in degrees) to identify associations between the two zones.

The secondary variables involve critical tilt angles for water spillage: To assess the practical implications of positional stability in lifting tasks, this study calculates critical tilt angles at which water would spill from the box when filled to different levels. Since the boxes in Figure 4 are not filled with water during testing, a hypothetical model predicts tilt angles leading to spillage at various fill levels (1 cm to 5 cm below the top edge), as shown in Figure 5.

Using trigonometry (arctangent function), the model links water height to box width to determine precise tilt angles. For example, if the water level is 2 cm below the top edge, the maximum posterior tilt before spillage is 7.63°. Exceeding this angle would likely cause spillage.

These calculated tilt angles serve as reference points to interpret children's lifting performance. Comparing their measurements with these angles helps assess their ability to control stability, a crucial skill in real-life activities.

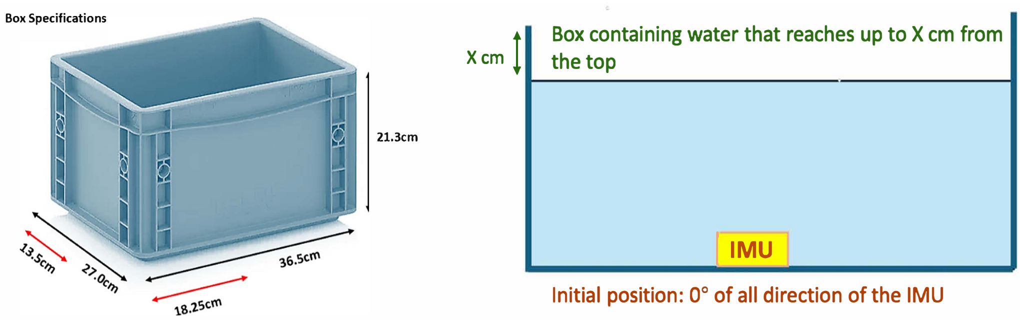

Figure 4. Box specification and simulated water fill levels.

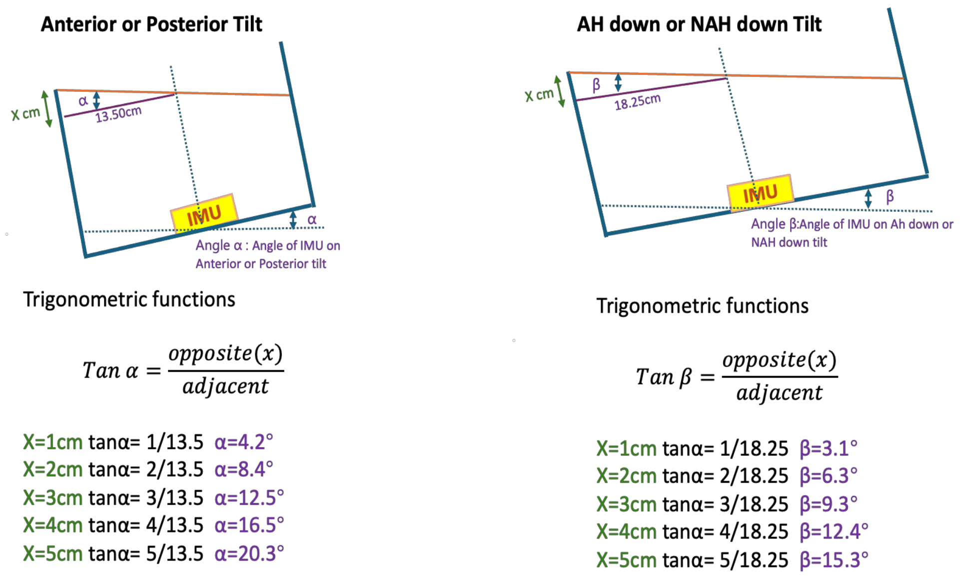

Figure 5. Water spilling angles with different tilt directions. Note: The calculation was not made for the AH/NAH forward rotation because movement in the horizontal plane is not very relevant as parameter causing spilling.

2.6. Data Collection

Each measurement consisted of three MVC attempts, each lasting five seconds. The program identified the maximum weight within these intervals to pinpoint the three MVC attempts per test. From each peak, the program searched back to find the start of each attempt, marked when the weight dropped below 0.20 kg. Similarly, it searched forward from the peak to identify the end of the attempt using the same threshold criterion.

In each attempt, there are two key areas of interest: the lifting period and the maximal contraction period. The lifting period, called the SubMax zone, is defined as the time from when the weight first exceeds the threshold value to when it reaches 80% of its maximum value. The maximal contraction period, called the Max zone, is when the weight consistently exceeds 80% of its maximum value.

Raw data from the ADL-TTD was exported to Excel for further analysis using the programming language Python, Version 3.8, Available online: https://www.python.org/. The Python program imported raw data and converted the quaternion orientation measures into Euler angles for a more intuitive analysis of spatial orientation. To remove extremely large outliers from sudden bursts of effort (e.g., abrupt lifting movements), a 0.99 quantile filter was applied to the weight variable. The outliers refer to data points that lie beyond a specified quantile threshold. This threshold was selected because it effectively removes extreme spikes in the data while preserving the overall strength profile, ensuring that the maximal strength value remains largely unaffected.

The Python program determined the MVC and the average tilt angle along the x-, y-, and z axes for the SubMax and Max zones. Each measurement includes data from three different attempts, from which the average is calculated. If one attempt is deemed incorrect, the average is recalculated from the remaining two attempts. Based on consensus, an attempt is incorrect if the deviation between MVCs is greater than 20% [22]. To ensure the accuracy of the automated scoring system, results were compared with manuallyscored data from five participants, and the outcomes were found to be similar, confirming the reliability of the automated approach.

2.7. Statistical Analyses

2.7.1. Descriptive Statistics

Participant demographics and baseline characteristics (e.g., age, sex, diagnosis, classification systems) will be summarized using means and standard deviations (SD) for continuous variables and frequencies and percentages for categorical variables. Summaries will be provided for the full sample and by levels of force control (Max and SubMax zones).

2.7.2. Hypothesis Testing

- Primary Hypothesis: Differences in positional performance between Max and SubMax zones will be assessed using the Wilcoxon signed-rank test.
- Secondary Hypothesis: Group differences (USCP vs. Non-USCP) in positional performance and spillage rates will be analyzed using the Kruskal–Wallis test.
- Tertiary Hypothesis: Correlations between Max and SubMax zones across positional parameters will be evaluated using Spearman's rank correlation.

2.7.3. Significance Testing

A significance level of $p < 0.05$ will be applied. Analyses will be performed using SPSS version 29.0.1 (IBM SPSS, IBM Corp, Armonk, NY, USA).

3. Results

In this study, data from 83 children and adolescents were included. These children were diagnosed with USCP, bilateral cerebral palsy (BCP), dyskinetic cerebral palsy, spina bifida, and other syndromes. The participants were divided into two subgroups: the USCP group (n = 62), consisting of children diagnosed with USCP, and the Non-USCP group (n = 21), consisting of children with other diagnoses. Table 1 shows the characteristics of the participants.

The sample size for this study (n = 83) was determined by the availability of participants who met the inclusion criteria. While no formal power analysis was conducted, the sample size is comparable to that in similar studies involving children with neurodevelopmental and motor disabilities in real clinical situations.

Table 1. Population characteristics and distributions. Note: MACS: Manual Ability Classification System GMFCS, classification of hand function in children with CP (I–V, from best to most limited); Gross Motor Function Classification System MACS, classification of gross motor function in CP (I–V, from most independent to most limited).

Population	Number	Age (Mean ± Std)	MACS Distribution	GMFCS Distribution	Sex Distribution	Affected Side
USCP	62	13.35 ± 2.67	1:20 2:31 3:9	1:48 2:12 3:2	Male: 30 (48.4%) Female: 32 (51.6%)	Right: 39 (62.9%) Left: 23 (37.1%)
Non-USCP	21	15.86 ± 1.93	1:16 2:5	1:13 2:3 3:1 4:3 5:1	Male: 14 (66.7%) Female: 7 (33.3%)	Right: 9 (42.9%) Left: 12 (57.1%)
All	83	13.99 ± 2.73	1:38 2:36 3:9	1:61 2:15 3:3 4:3 5:1	Male: 44 (53.0%) Female: 39 (47.0%)	Right: 48 (57.9%) Left: 35 (42.1%)

The results of the study, measured through the ADL-TTD, provide critical insights into the positional performance, spillage prevention, and strength performance of children with neurodevelopmental disabilities during bimanual lifting tasks across different levels of force control. For spilling in different directions within individual children during the lifting task, we find that most children will not spill water in any direction when the water level is below 3 cm from the top of the box. Figure 6 shows the individual performances.

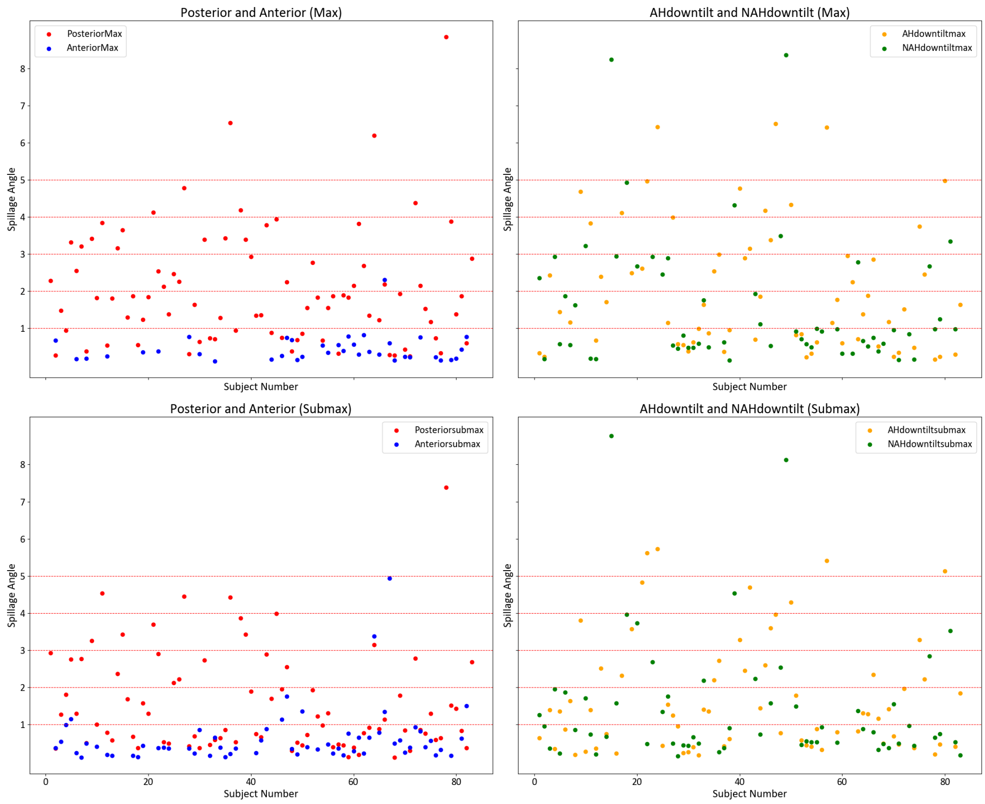

Figure 6. Scatter plot for individual subjects in all directions in the Max and SubMax zones. Note: Red dash lines mean different water levels below the top of the box.

3.1. The Primary Hypothesis

The primary hypothesis tested whether positional performance in the Max zone would be worse than in the SubMax zone across at least four of the six positional parameters. The results, presented in Table 2, indicate the following: Median values for posterior tilt decreased significantly in the Max zone (7.68, IQR 3.45–11.91) compared to the SubMax zone (4.18, IQR 0.72–7.64); ($p < 0.05$). Similarly, NAH forward rotation showed a significant decrease in the Max zone (3.04, IQR 0.85–5.23) compared to the SubMax zone (2.39, IQR 0.75–4.02); ($p < 0.05$). Median values for NAH down tilt decreased from 2.87 (IQR −0.16–5.90) in the Max zone to 2.29 (IQR 0.39–4.20) in the SubMax zone, and AH down tilt decreased from 4.73 (IQR 1.03–8.43) to 3.52 (IQR 0.47–6.57), but these differences were not statistically significant ($P = 0.162$ and $P = 0.278$, respectively). In contrast, median values for anterior tilt increased significantly from 1.10 (IQR 0.22–1.97) in the Max zone to 1.58 (IQR 0.63–2.53) in the SubMax zone ($P = 0.019$), and AH forward rotation also increased significantly from 1.19 (IQR 0.46–1.93) in the Max zone to 1.32 (IQR 0.46–2.17; $P = 0.045$). Overall, four out of six positional parameters showed worse performance in the Max zone compared to the SubMax zone. However, only two differences (posterior tilt and NAH forward rotation) were statistically significant ($p < 0.05$).

Table 2. Comparison of Max and SubMax Values Using Wilcoxon signed-rank test.

Parameter	Max (N)	Max Median (IQR)	SubMax (N)	SubMax Median (IQR)	p-Value
Posterior	83	7.68 (3.45–11.91)	82	4.18 (0.72–7.64)	0.000 *
Anterior	37	1.10 (0.22–1.97)	61	1.58 (0.63–2.53)	0.019 *
NAH Forward Rotation	78	3.04 (0.85–5.23)	79	2.39 (0.75–4.02)	0.000 *
AH Forward Rotation	48	1.19 (0.46–1.93)	65	1.32 (0.46–2.17)	0.045 *
AH Down Tilt	65	4.73 (1.03–8.43)	68	3.52 (0.47–6.57)	0.278
NAH Down Tilt	57	2.87 (−0.16–5.90)	59	2.29 (0.39–4.20)	0.162

Note: * $p < 0.05$.

Spillage prevention rates increased progressively with the distance of the water level from the box top, as shown in Table 3. At the highest water level (1 cm), only 16.9% of all participants avoided spilling in the Max zone and 25.3% of all participants avoided spilling in the SubMax zone. At the lowest water level (5 cm), spillage prevention rates improved to 91.6% in the Max zone and 95.8% in SubMax zone. The SubMax zone consistently showed slightly higher spillage prevention rates than the Max zone at all water levels. The Max zone exhibited worse positional performance in four out of six parameters compared to the SubMax zone. Spillage prevention rates were lower in the Max zone at all water levels.

Table 3. Comparison of water levels among USCP, non-USCP, and all populations.

Water Level (cm)	USCP (62)		Non-USCP (21)		All Population (83)	
	Max Zone (N (%))	SubMax	Max Zone (N (%))	SubMax	Max Zone (N (%))	SubMax
1	7 (12.5%)	10 (17.9%)	5 (23.8%)	4 (19.05%)	14 (16.9%)	21 (25.3%)
2	16 (28.6%)	21 (37.5%)	8 (38.1%)	10 (47.6%)	28 (33.7%)	38 (45.8%)
3	29 (51.8%)	36 (64.3%)	14 (66.7%)	15 (71.4%)	48 (57.8%)	57 (68.7%)
4	40 (71.4%)	45 (80.4%)	17 (81.0%)	18 (85.7%)	63 (75.9%)	69 (83.1%)
5	51 (91.1%)	52 (92.9%)	19 (90.5%)	19 (90.5%)	76 (91.6%)	77 (92.8%)

3.2. The Secondary Hypothesis

The results of the secondary hypothesis reveal the following: In the Max zone, median values for posterior tilt, NAH forward rotation, AH forward rotation, AH down tilt, and NAH down tilt were lower in the non-USCP group than in the USCP group, but these differences were not statistically significant. In the SubMax zone, median values for posterior tilt, NAH forward rotation, AH down tilt, and NAH down tilt also decreased in the non-USCP group relative to the USCP group, but, again, these differences were not statistically significant.

The remaining parameters showed non-statistically-significant increases in the non-USCP group compared to the USCP group in both zones. Overall, no positional parameters exhibited statistically significant differences between the USCP and non-USCP groups.

As shown in Table 3, spillage prevention rates were higher in the non-USCP group compared to the USCP group at all water levels: At the highest water level (1 cm), 12.5% of USCP participants avoided spilling in the Max zone, compared to 23.8% of non-USCP participants. At the lowest water level (5 cm), spillage prevention rates increased to 91.1% in the USCP group and 90.5% in the non-USCP group for the Max zone.

No significant differences in positional performance were observed between the USCP and non-USCP groups, which agrees with the null hypothesis for this aspect of the analysis, as shown in Table 4. While spillage prevention rates were generally higher in the non-USCP group than in the USCP group, the differences were small and not statistically significant, further supporting the null hypothesis. Overall, while the non-USCP group performed slightly better in both positional parameters and spillage prevention rates, these differences were not strong enough to reject the null hypothesis.

Table 4. Comparison of median (IQR) between USCP and non-USCP groups.

Variable	Median (IQR) USCP	Median (IQR) Non-USCP	p-Value	N USCP	N Non-USCP
MVC	8.18 (3.73–12.63)	10.48 (7.96-15.09)	0.15	62	21
Posterior Max	7.75 (3.42–12.09)	5.68 (2.53–9.19)	0.31	62	21
Anterior Max	1.1 (0.19–2.0)	1.11 (0.71–2.36)	0.73	23	14
NAH Forward Rotation Max	3.42 (0.61–6.23)	2.31 (1.18–3.78)	0.15	58	20
AH Forward Rotation Max	1.3 (0.26–2.34)	0.81 (0.67–1.27)	0.15	34	14
AH Down Tilt Max	5.45 (1.63–9.28)	3.67 (1.10–5.85)	0.15	48	17
NAH Down Tilt Max	2.87 (−0.18–5.92)	2.64 (0.84–3.51)	0.40	42	15
Posterior SubMax	4.4 (0.61–8.18)	3.78 (3.07–6.67)	0.97	62	20
Anterior SubMax	1.51 (0.75–2.26)	2.55 (1.61–3.80)	0.05	43	18
NAH Forward Rotation SubMax	2.81 (0.52–5.1)	1.74 (1.39–2.69)	0.04	58	21
AH Forward Rotation SubMax	1.29 (0.29–2.3)	1.34 (0.54–1.63)	0.17	48	17
AH Down Tilt SubMax	3.59 (0.21–6.97)	3.52 (1.44–5.71)	0.60	50	18
NAH Down Tilt SubMax	2.29 (0.11–4.47)	2.18 (1.44–3.33)	0.57	43	16

3.3. The Third Hypothesis

From the results of the third hypothesis shown in Figure 7, we observe that all position parameters correlate positively between the Max and Submax zones. Among these, the AH down tilt position has the strongest positive correlation coefficient (0.86), while the anterior tilt has the weakest (0.31). The other positioning parameters also correlate well, each with a coefficient above 0.6. The results support the alternative hypothesis (H_a), indicating that most positional variables correlate strongly between the Max and SubMax zones. This highlights the consistency in positional performance across different levels of force control. Overall, these results reject our H_0 hypothesis that there is no strong positive correlation between most of the variables (less than four with coefficients ≤ 0.6). Table 5 shows all the Spearman correlation values.

Table 5. Spearman correlation between Max and SubMax zones for the whole group.

Max Zone	SubMax Zone	Spearman Correlation
Posterior Tilt	Posterior Tilt	0.74
Anterior Tilt	Anterior Tilt	0.31
NAH Forward Rotation	NAH Forward Rotation	0.69
AH Forward Rotation	AH Forward Rotation	0.70
AH Down Tilt	AH Down Tilt	0.86
NAH Down Tilt	NAH Down Tilt	0.81

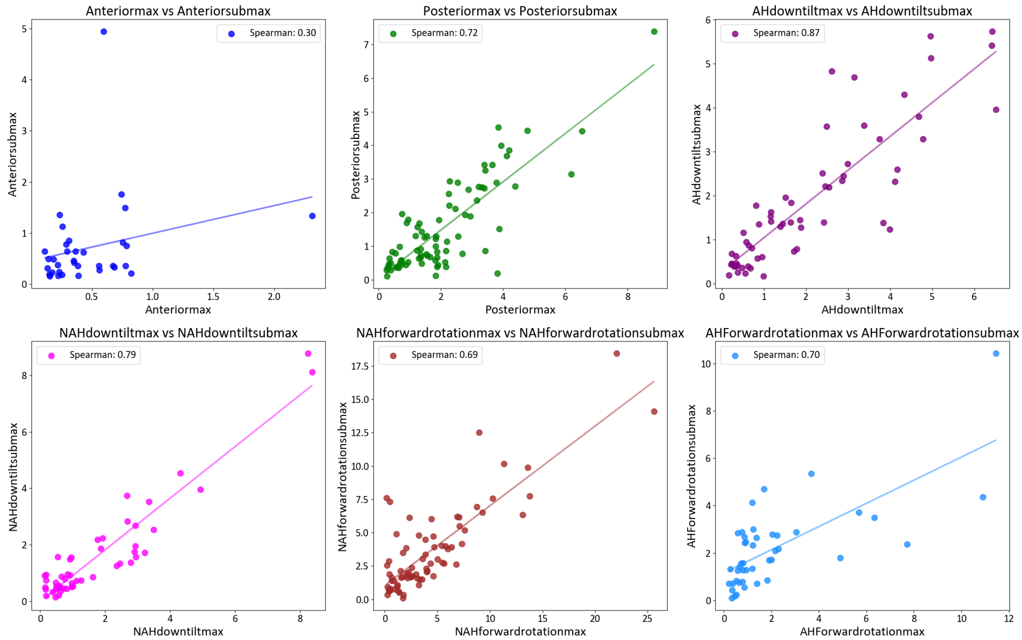

Figure 7. Scatter plot of all the position variables between the Max and SubMax zones.

4. Discussion

4.1. Impact of Levels of Force Control on Positional Performance and Spillage Prevention

The first and primary hypothesis aimed to investigate how task difficulty, represented by maximal (Max) and submaximal (SubMax) levels of force control, affects positional performance and spillage prevention during bimanual lifting tasks in children with neurodevelopmental disabilities. The results supported the alternative hypothesis (H_a), showing that four out of six positional parameters showed worse performance in the Max zone than in the SubMax zone. The results indicate that maximal levels of force control pose greater challenges in maintaining positional performance and preventing spillage than the submaximal zones. Comparing with the literature, Basu's findings align closely with our results, showing that deviations in the affected hand significantly affect bimanual task performance in children with USCP, particularly under conditions that strain their capabilities [12]. Kim et al. (2020) found that when exertion levels increase, maintaining stability in bimanual tasks becomes more challenging [23]. Similarly, Miller et al. (2020) reported that maximal exertion leads to greater neuromuscular fatigue and impaired motor control compared to submaximal conditions [24]. These findings suggest that maximal levels of force control conditions impose greater challenges on children with USCP, leading to instability and reduced control, particularly in bimanual tasks. Moreover, Swift et al. (2022) found no significant performance decline between submaximal efforts and lower weight conditions, contrasting with our findings under maximal conditions. A key difference is the study population—ours focuses on children with neurodevelopmental impairments, while Swift et al. (2022) examined healthy individuals [25]. Overall, the findings confirm that levels of force control significantly affect positional performance and spillage prevention, with maximal zones presenting greater challenges than submaximal zones.

Another point is that the small differences observed in AH down tilt and NAH down tilt across Max and SubMax zones may be due to the following reasons: During bimanual lifting, the body naturally distributes weight evenly, reducing the need for large side-to-side tilts [26]. Since both hands are engaged equally, bilateral coordination minimizes asymmetrical shifts, making left and right tilt less affected by increased effort [27]. Additionally, sagittal plane movements (anterior/posterior tilt) require greater postural adjustments, as they involve larger neuromuscular activation, leading to more noticeable differences under different levels of force control [28].

4.2. Differences in Object Positioning Between USCP and Non-USCP Groups

The second hypothesis of this study aimed to determine whether object positioning parameters differ between the USCP and non-USCP groups during bimanual lifting tasks. This analysis is particularly relevant for understanding how motor impairments associated with USCP affect performance across the Max and SubMax levels of force control. The results showed no statistically significant differences in positional performance parameters between the USCP and non-USCP groups in either the Max or SubMax zones, suggesting that both groups perform similarly under controlled conditions. Nine parameters demonstrated better positioning performance in the SubMax zone than the Max zone across both groups. Analysis of variability, as measured by the interquartile range (IQR) of tilt angles, revealed important distinctions. The USCP group exhibited higher variability than the non-USCP group across both zones, as shown by higher IQR values. This indicates greater variation in their ability to control tilt during these tasks. These findings align with those of Pavão et al. (2015), who noted that children with USCP often adopt unique motor control strategies in coordinated tasks [29]. Such variability may reflect adaptive strategies or compensatory mechanisms employed by the USCP group to overcome their motor impairments. The non-USCP group, lacking these impairments, exhibited a more consistent performance across most tasks. Increased variability likely stems from neuromuscular and motor control impairments, as supported by prior studies [29,30], which showed that children with CP exhibit decreased precision and efficiency in upper limb tasks. In addition to positional performance, spillage prevention rates also differed slightly between the groups. Spillage prevention was consistently better in the SubMax zone for both groups, with the non-USCP group showing a slight but consistent advantage at all water levels.

4.3. Correlation Between Maximal and Submaximal Performance

Our third hypothesis, which expected a positive correlation between performance in the maximal and submaximal zones, was largely supported by the data. H_0 was rejected, as strong positive correlations were seen for parameters like posterior tilt, NAH forward rotation, AH down tilt, and NAH down tilt (coefficients ≥ 0.83). AH forward rotation showed a moderate correlation (0.70), while anterior tilt had the weakest but still a fair correlation (0.31), which is consistent with guidelines for interpreting correlation coefficients [31]. This consistency shows that performance in submaximal conditions can predict performance in maximal conditions, which is important for creating effective rehabilitation plans. These results align with studies such as Miller et al. (2020), which demonstrated that both maximal and submaximal exertions impose a comparable neuromuscular burden, supporting the idea that performance remains stable across strength levels [24]. Similarly, Swift et al. (2022) found no significant performance decline between submaximal (around 50% MVC) and lower weight conditions in crate-lifting tasks which is consistent with our findings that submaximal assessments can predict maximal performance in functional tasks [25]. Further, one study suggests that individuals adjust their neuromuscular responses according to anticipated loads, even in submaximal, non-fatiguing conditions, leading to movement patterns similar to those observed in maximal lifts, further corroborating our results [32]. This study reveals for the first time the relationship in performance between maximal and submaximal effort in a bimanual lifting task. These findings largely reject our H_0 hypothesis , indicating that monitoring performance in submaximal conditions can reliably predict performance under maximal conditions for most directions measured. In clinical implementation, the strong positive correlations for most positioning parameters suggest that submaximal performance can reliably predict maximal performance. Assessing submaximal movements in patients could provide valuable insights into their capacity for maximal levels of force control .

4.4. Clinical Implications and Technological Advancements in Rehabilitation

This study offers key insights into how both maximal and submaximal functional levels of force control affect task performance, particularly for individuals with upper extremity physical disabilities. To prevent performance declines, it highlights the need for personalized rehabilitation programs that address various levels of force control and emphasize not just strength development but also the stability and control required for high-intensity tasks.

By incorporating innovative technology such as IMU sensors, this study give a fresh perspective on task performance. It moves beyond assessing body movements alone to exploring how individuals interact with objects during functional activities. For instance, using a box filled with water as part of the experimental setup reveals critical dynamics in object manipulation during everyday tasks, such as maintaining control to prevent spillage. This focus on object interaction enhances our understanding of the challenges associated with tasks that demand precision and stability.

The findings also highlight the value of submaximal performance as a reliable predictor of maximal levels of force control, making it a practical tool for evaluating abilities and tailoring rehabilitation. The observed variability in performance, particularly among individuals with USCP, emphasizes the importance of addressing motor control strategies and variability to improve both precision and consistency during task execution.

4.5. Strengths and Limitations

This study evaluates both maximal contraction (MaxZone) and submaximal contraction (SubMax zone) during the box-lifting task. This allows for a thorough understanding of performance across different levels of force control, which can help in assessing functional capabilities more widely. The study employs IMUs to measure positional performance in terms of tilt along the x-, y-, and z axes. These devices offer precise and objective data on positional changes during lifting tasks. Automating the data analysis by programming makes it more efficient. Six specific parameters (anterior and posterior tilt, AH/NAH forward rotation, and AH/NAH downward tilt) are assessed, offering a targeted approach to understanding how positional performance changes between the Max and SubMax zones. The study focuses on a population of children aged 12–18 years with neurodevelopmental disabilities, providing valuable insights into motor control challenges in this specific group. This is an exploratory study with a small sample, and the representation of different subgroups (e.g., children with different neurodevelopmental conditions) may be uneven. This could affect its statistical power, and the conclusions should be interpreted with caution. In addition, the study focuses on a single, specific task (box lifting), which may not capture the full range of functional movements and challenges that children with neurodevelopmental disabilities encounter in their daily lives.

5. Conclusions

This study shows that maximal tasks increase instability and variability, while submaximal tasks show higher consistency and spillage prevention in individuals with upper extremity disabilities. The strong correlation between levels of force control suggests that submaximal assessments can safely predict maximal performance. The findings highlight the need for positional performance-based rehabilitation to enhance functional outcomes and independence.

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Abbreviations

The following abbreviations are used in this manuscript:

USCP	Unilateral Spastic Cerebral Palsy
MVC	Maximum Voluntary Contraction
ADL	Activity of Daily Living
IMUs	Inertial Measurement Units
AH	Affected Hand
NAH	Non-Affected Hand
ADL-TTD	Activity of Daily Living Testing and Training Device
SD	Standard Deviations
BCP	Bilateral Cerebral Palsy
MACS	Manual Ability Classification System
GMFCS	Gross Motor Function Classification System
IQR	Inter Quartile Range
UE	Upper Extremity

Appendix A

Table A1. Device specifications.

Specification	Value
Dimensions (L × W × H)	180 × 100 × 80 cm
Height adjustment range	60–120 cm (height of tabletop)
Weight of device	75 kg
Accuracy of lifting (height)	±2 mm
Accuracy of lifting (weight)	To lift 5 kg: ±10 g From 5 kg to 40 kg: ±0.5%
Maximum lifting height from tabletop	70 cm
Maximum lifting weight	40 kg
Power supply	240 V, 50/60 Hz

Table A2. Specifications of Adafruit BNO055 Absolute Orientation Sensor.

Measurement	Specifications
Absolute Orientation (Euler)	→ Euler Vector, 100 Hz Three-axis orientation data based on a 360° sphere
Absolute Orientation (Quaternion)	→ Quaternion, 100 Hz Four-point quaternion output for more accurate data manipulation
Angular Velocity Vector	→ 100 Hz Three-axis rotation speed in rad/s
Acceleration Vector	→ 100 Hz Three-axis acceleration (gravity + linear motion) in m/s^2
Magnetic Field Strength Vector	→ 20 Hz Three-axis magnetic field sensing in microteslas (µT)
Linear Acceleration Vector	→ 100 Hz Three-axis linear acceleration data (acceleration minus gravity) in m/s^2
Gravity Vector	→ 100 Hz Three-axis gravitational acceleration (minus any movement) in m/s^2
Temperature	→ 1 Hz Ambient temperature in degrees Celsius

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