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# Spatiotemporal kinematic parameters reflect spasticity level during forward reaching in children with hemiplegic cerebral palsy: correlation and regression analysis

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**Literature has identified disparities in reaching patterns between children with cerebral palsy and typically developing children. However, determining the spatiotemporal parameters that effectively quantify upper limb motor performance and examining the relationship between these parameters and spasticity level remains a challenge. This study aimed to investigate the relationship between the level of spasticity and the spatiotemporal parameters and detect which parameter is the most influenced by spasticity level. Fifty children with hemiplegic cerebral palsy participated and were asked to reach forward, at a self-selected pace, toward one target at a normalized distance under one level of accuracy. An optoelectronic system captured three-dimensional spatiotemporal parameters quantifying the movement time, velocity, strategy and smoothness of forward reaching. Spearman rank correlation coefficient was used to investigate the strength of the relationship between the level of spasticity and the spatiotemporal parameters ($P^{<}0.05$). Regression analysis was used to model the relationship between the studied variables and to investigate the impact of spasticity on the studied kinematic parameters. The level of spasticity was significantly correlated with normalized jerk score (NJS), number of movement units and peak velocity respectively ($r$ = .0.7–0.8). The regression model was statistically significant ($p < .001$), and explained a significant proportion of the variances of the studied parameters especially NJS ($R^2 = 0.972$) and NMU ($R^2 = 0.953$). NJS is the most influenced parameter by the level of spasticity; therefore, it can be used as an index to quantify the impact of spasticity on reaching performance and to evaluate the effectiveness of treatment strategies on motor recovery.**

**Keywords** Hemiplegic cerebral palsy, Spasticity, Reaching, Motion analysis, Spatiotemporal parameters, Correlation, Regression analysis

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Cerebral palsy (CP) is defined as a non-progressive lesion to the brain that occurs during fetal or infantile development, resulting in a range of movement and postural problems[1,2]. Children with cerebral palsy show insufficient coordination in movement, which may be owing to accompanying deficits such as stiffness, muscular weakness, sensory problems, and range of motion limits[1].

Reaching is a movement towards a given target and represents an important multi-joint coordination of the upper extremities[3,4]. One of the activity limitations in children with hemiplegic CP involves the performance of manual reaching[5,6], which is essential to the development of manipulative and routine daily activities[4,7]. Some previous Studies have proved that reaching movements in children with CP showed spatiotemporal changes compared to the typically developing children[8]. Other studies have confirmed electromyographic alterations[9], and postural control deficits[8]. These changes are likely to contribute to difficulties in accomplishing activities such as feeding, dressing, writing, and playing with other children, thus leading to reduced participation in social contexts[2].

Reaching reflects coordination between multiple joints and involvement of both the musculoskeletal and neural system[10,11]. Thus, it is necessary to evaluate reaching with a quantitative method for rehabilitation practitioners and researchers to objectively describe the multiple joint coordination and functional status of the impaired upper limb and to discriminate between healthy and pathological conditions. That could help in the decision-making process in clinical setting and monitoring the outcomes during rehabilitation and treatment protocol[12–14].

Kinematic analysis of upper limb tasks is considered the gold standard for the evaluation of motor performance[15] and provides accurate, reliable, quantitative, valid and sensitive data to quantify the level of motor performance of individuals with movement disorders[16]. There are many kinematic variables utilized to quantify characteristics of reaching such as movement units (MU), movement time (MT), peak velocity (PV) and normalized jerk score (NJS) in different populations during reaching[17,18].

One challenge is to identify the kinematic variables that best quantify upper extremity movements in children with hemiplegic CP because of many factors such as spasticity which is a common motor impairment in patients with upper motor neuron lesions. Spasticity is defined as increasing resistance to increasing speed of stretch relative to the direction of joint movement[19,20]. Spasticity has been commonly measured clinically by rating scales such as Modified Ashworth Scale (MAS). One of the limitations of using these clinical rating scales is that these scales can provide categorical measurement of the dysfunction only and cannot detect small changes that occur as a result of treatment or over time. Kinematic analysis has the advantage of being a quantitative and more objective measure than clinical rating scales as it is more sensitive to minimal changes that occur and it can be monitored more closely than the clinical rating scores.

The purpose of this study is to investigate the relation between the level of spasticity measured by the Modified Ashworth Scale (MAS) and the spatiotemporal kinematic parameters of the forward-reaching task. The research questions of this study are: (I) Is there any correlation between spasticity and the spatiotemporal kinematic parameters of reaching in children with hemiplegic CP? And if yes, then (II) which parameter is highly influenced by spasticity level?

## Methods

### Sample size calculation

A Priori sample size calculation was performed using G*Power 3.1.9.4 software (Heinrich-Heine Universität Düsseldorf, Düsseldorf, Germany; http://www.gpower.hhu.de/). The alpha level was set at $\alpha = 0.05$, the statistical power was set at 80%; the confidence level of 95% and the effect size of 0.5 according to Cohen's guidelines for interpreting the effect size for correlation[21] and the statistical test was set at (correlation: bivariate normal model). The minimum sample size was estimated to be 35 participants; however, a sample size of 50 participants was recruited considering 10–15% dropout rate.

### Participants

A convenience sample of fifty Participants with hemiplegic CP was recruited from the university hospitals' outpatient rehabilitation clinics from January till July 2024. The participants aged from 5 to 7 years ($6.49 \pm 0.47$ years). The flowchart of the study participants is shown in Fig. 1. Demographic and clinical characteristics of the study participants are displayed in Table 1.

Participants were selected based on the following inclusion criteria:

(1) The participants were diagnosed with congenital hemiplegic cerebral palsy aged 5–7 years by an experienced Paediatric neurologist who was blinded to the study objectives (2) the degree of spasticity ranged between (Grades 1–2) on the modified Ashworth scale (MAS), (3) They can sit, stand, and walk independently with adequate balance control.

The current study targeted this age range (5-7 years), because, at this age, it's often possible to differentiate more clearly between the typically developed and the atypically developed children. This age range allows clinicians to undertake more comprehensive assessments of motor skills, particularly upper limb function and gross motor abilities[22].

Participants were excluded if they had: (1) visual, cognitive, perceptual, or auditory defects that could interfere with the assessment processes; (2) any other neurological condition that could interfere with movement ; (3) any involuntary movement or dystonic features; (4) they were also excluded if they had a previous history of surgical intervention or Botulinum toxin type-A (BTX-A) injection in the affected upper extremity in the previous 12 months; (5) any permanent structural deformity in the affected upper limb leading to limitation of ROM or using any upper limb orthotics.

The current study was approved by the Research Ethical Committee of the Faculty of Physical Therapy, South Valley University with the following number (PT-ORT 05–2024-543). The current study was carried out

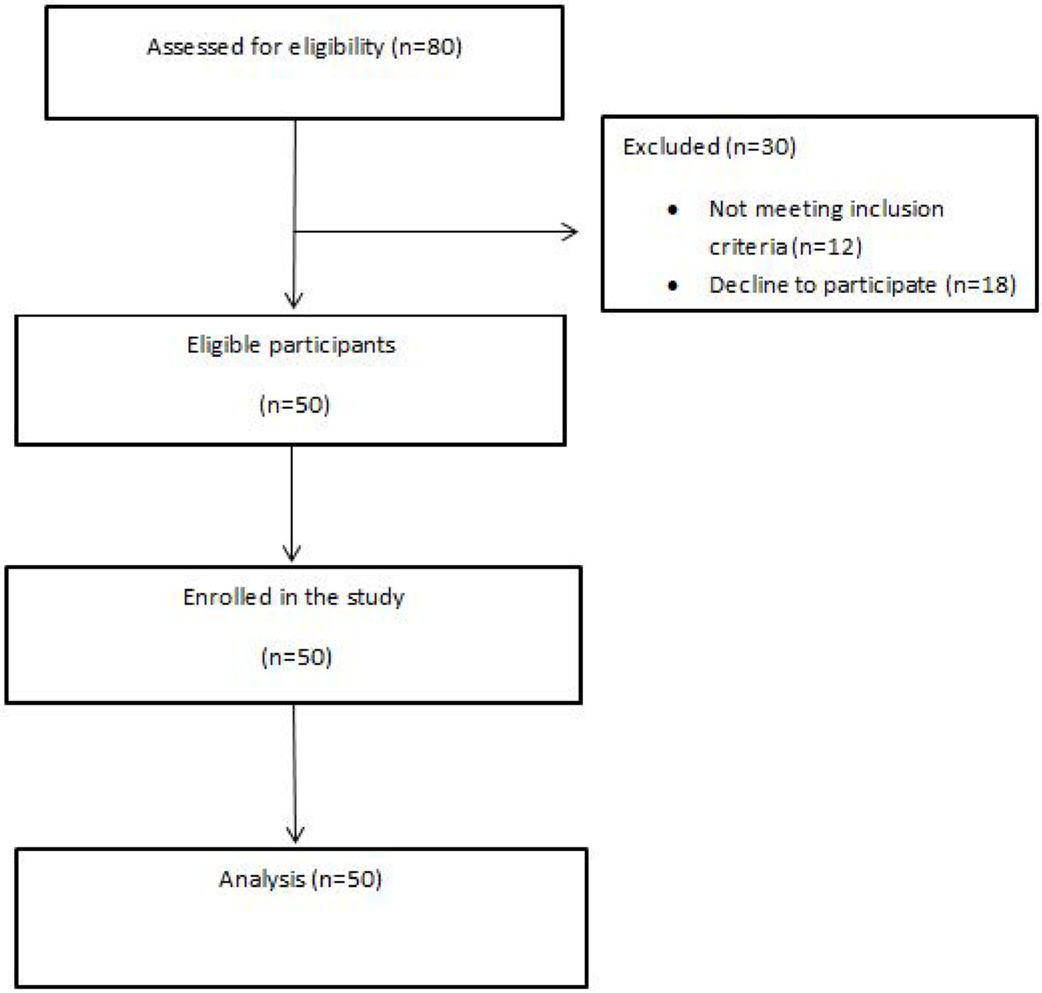



**Fig. 1**. Flowchart of the study participants.

following the guidelines of the World Medical Association Declaration of Helsinki. An informed consent was obtained from all the participants' legal guardians before participation in the study. All the study objectives and procedures were explained to the participant's caregivers before participation in the study.

## Materials and instrumentations

To enhance trunk stability and avoid compensatory trunk movement during the forward reaching task, a height-adjustable chair (allowing 90 degrees of knee and hip joint flexion with feet on the floor) was used in conjunction with a harness fastened bilaterally in the chair back. A height-adjustable table was positioned in front of the participant, on which a 4 $cm^3$ block was fixed upright, adjusted to be at the level of the sternal notch, and placed along the sagittal plane at a distance standardized for each subject's upper limb length ( measured from the axilla's medial border to the tip of the middle finger). The ProReflex motion capture system (Qualisys Medical AB, Gothenburg, Sweden) was utilized to track the markers' movements during reaching movement using three cameras (240 HZ) that track the displacement of reflecting markers.

Passive reflective markers were placed as follows: over the index fingertip; over the Dorsal aspect of the third metacarpal head; over the dorsal centre of the wrist, and top of the target (block) (Fig. 2).

The cameras were placed two meters away from the experimental space because Camera placement can affect the accuracy of the kinematic data collected. Being too close may result in distortion of images while being too far could lead to loss of detail and resolution. The 2-m distance is often found to strike a balance that minimizes these issues and enhances the quality of the motion capture data[23] (Fig. 3). The sampling rate was set to 60 HZ, and raw data were filtered using a second-order forward and backward Butterworth filter with a cut-off frequency of 5 HZ.

## Experimental protocol

The Modified Ashworth Scale (MAS) was used to assess upper-extremity muscular tone in each participant. Assessment of muscle tone was done by an experienced senior physiotherapist with clinical experience of more

| Demographics | Descriptive statistics |
|---|---|
| Age (years) | 6.49 ± 0.47 |
| Gender | |
| Male | 23 (46%) |
| Female | 27 (54%) |
| Affected upper limb | |
| RT side | 28 (56%) |
| Lt side | 22 (44%) |
| MASEF | |
| G 1 | 15 (30%) |
| G 1 + | 20 (40%) |
| G 2 | 15 (30%) |
| MASWF | |
| G1 | 14 (28%) |
| G1 + | 19 (38%) |
| G2 | 17 (34%) |

**Table 1**. Demographic and clinical characteristics for the study participants (n = 50). Continuous data are expressed as mean ± SD; Categorical data are expressed as absolute number (%). MASEF: modified Ashworth score of elbow flexors; MASWF: modified Ashworth score of wrist flexors; G: grade; RT: right; LT: left.

**Fig. 2**. Marker placement sites on the wrist and hand (left) and before touching the target (right).

**Fig. 3**. Camera placement in the experimental space in the motion analysis unit.

than 18 years in Paediatric physical therapy. This examiner was blinded to the study objectives and his only role was to evaluate the muscle tone of the participants and record it in the evaluation sheet. MAS is a six-point rating scale for assessing spasticity with good validity and inter-rater reliability[24].

The upper extremity level of spasticity in the current study was rated according to the elbow flexors muscle tone, because, the spasticity of elbow flexors presents a more substantial challenge to the spatiotemporal aspects of upper limb reaching compared to wrist flexors. The spasticity of wrist flexors primarily influences hand positioning and grasping but does not significantly restrict the overall reaching movement as much as the elbow flexors do[25,26]. The experimental protocol in the current study was designed to be minimally invasive through the use of non-invasive technologies, considering the participants' comfort, and efficient procedures.

To normalize the participants' relative initial testing posture, participants were pleasantly positioned on a restricting seat in front of a height-adjustable table. Participants were instructed to sit upright with their sternoclavicular notch aligned with the target. To prevent excessive trunk movement and to improve the reaching performance, the trunk was constrained with harness equipment[27] as shown in Fig. 4.

The starting position was obtained by asking each participant to retain the affected upper extremity shoulder adducted to the trunk with the vertical upper arm in a relaxed position, elbow flexed to 90°, forearm pronation, and wrist in the neutral position and rested on the thig and the non-affected upper limb rested on the thigh as well. Before recording, each participant conducted two forward-reaching trials to ensure that the test task was thoroughly comprehended. When the order was given, each participant was instructed to reach forward to the target and contact it (the marker put on the top of the target) with the index finger by the affected hand at a self-selected pace, then return to the starting position (Fig. 2). Each subject performed 3 trials with (30 s) rest interval between trials to minimize fatigue effect[28]**.** Literature has shown that three trials can achieve good to excellent test–retest reliability for many kinematic variables in certain populations, such as individuals with motion impairments. This suggests that, under specific conditions, three trials may be sufficient for consistent measurements[29].

## Data processing

The skin marker on the dorsal aspect of the wrist was recognized across the captured range. Based on the previous literature, reaching movement could be captured by tracking the wrist marker displacement[30–32]. The fixed marker on the target was utilized to determine the precise timing of hand-target contact. The raw data from each camera was recorded on the computer and then transformed into three-dimensional (3D) (X, Y, Z) coordinates using the direct linear transform algorithm (Mac Reflex program), which is then analyzed offline using MATLAB (The Math Works Inc)software.

Spatiotemporal kinematic metrics can be utilized to quantify the reaching characteristics such as speed, force generation control strategy, and movement smoothness[30,33,34]. The movement time (MT) could depict the speed of reaching. Peak velocity (PV) was used to quantify force output. The percentage time to peak velocity (PTPV) could reflect the control strategy of reaching. The smoothness of movement was determined using the number of movement units (NMU) and the normalized jerk score (NJS)[14,16,30].

The movement smoothness of reaching paths in 3D space was determined by computing a time and distance normalized jerk score NJS for the wrist marker. Jerk is the change in acceleration per time. To eliminate its dramatic increase with movement duration, it must be normalized. Jerk normalization was performed using the following formula to obtain a quantity proportional to the absolute Jerk[35].

$$\text{NJS} = \sqrt{(1/2 * \int_{T\,start}^{T\,end} Jerk^2\,(t)\,dt) * duration^5 / length^2}$$

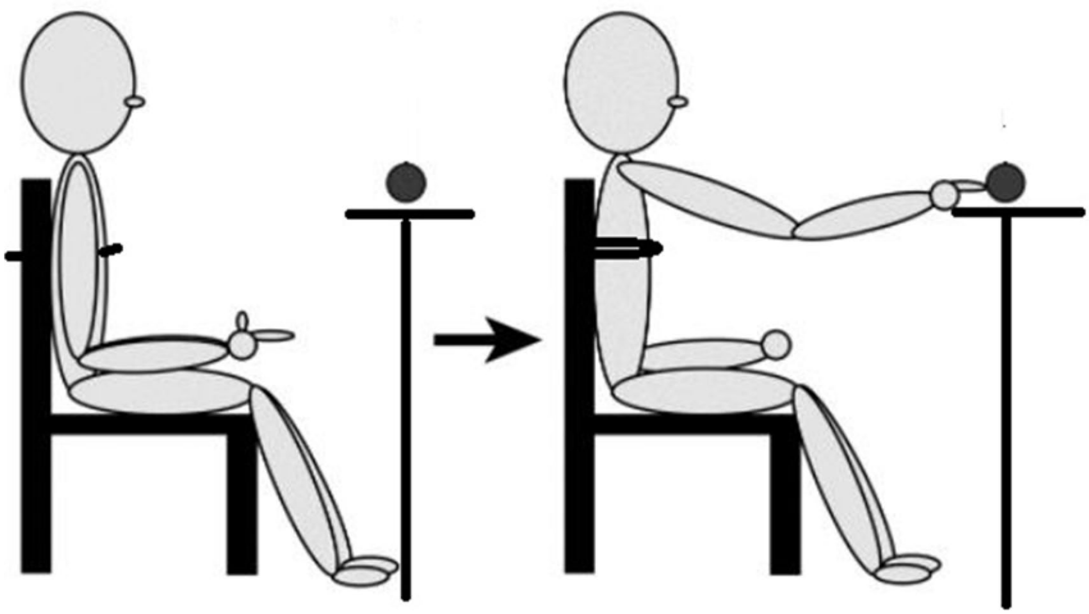


**Fig. 4**. schematic reaching task [starting position (left); end position (right)].

where:

$T_{START}$ and $T_{end}$: The start and end times of the movement,
Jerk: The 3rd time derivative of position data,
dt: The time difference($T_i - T_{i-1}$).
length: The movement amplitude.
duration: The movement execution time($T_{start} - T_{end}$).
The normalized jerk obtained is thus a dimensionless number[30,34].

The number of movement units (NMU) is another significant metric that represents movement smoothness. The NMU could be calculated by counting the number of acceleration-deceleration inflection points from the velocity profile[16,34] as shown in Fig. 5.

Normal smooth reaching is characterised by a single movement unit. One movement unit has only one accelerating phase and one deceleration phase. The number of movement units reflects the extent of error corrections throughout the movement and could be used to extrapolate the motor control strategy[33,34].

If the reaching is effectively controlled, the central nervous system (CNS) will not rely extensively on feedback loops to correct the ongoing movement errors. As a result, movement execution time will be reduced, force generation will be more engaged in movement, movement will become smoother (i.e., fewer movement units or lower normalized jerk score), and the percentage time to peak velocity will be higher (i.e., subject performs reaching with less dependence on on-line feedback for movement correction)[33]. We used the mean of the three trials for statistical analysis to obtain more stable and homogeneous spatiotemporal data.

## Statistical analysis

Statistical analysis was performed using the Statistical Package for the Social Sciences for Windows (SPSS version 23.0, IBM SPSS Incorporated, Chicago, IL, USA). The normality of data distribution was investigated using the Kolmogrove–Smirnov test, indicating that the data were not normally distributed ($P < 0.05$).

Spearman's rank correlation coefficient was used to investigate the strength of the relationship between the level of spasticity measured by the modified Ashworth scale (MAS) and the spatiotemporal parameters obtained by computerized upper limb motion analysis. Investigating the correlation between independent and dependent variables is an essential preliminary step before conducting regression analysis, as it provides critical insights into the relationships among variables. Correlation coefficients were interpreted as follows: 0.00–0.10 (0.00 to − 0.10) is considered as negligible correlation; 0.10–0.39 (− 0.10 to − 0.39) weak positive(negative) correlation; 0.40–0.69(− 0.40 to − 0.69) moderate positive(negative) correlation; 0.70–0.89(− 0.70 to − 0.89) strong positive(negative) correlation; and 0.90–1.00(− 0.90 to − 1.00) very strong positive(negative)[36].

A regression analysis was conducted using a generalized linear model (GLM) to model the relationship and assess the impact of the independent variable (spasticity level) on the studied dependent variables (spatiotemporal kinematic parameters). To run the regression analysis, the spasticity level measured by MAS was dummy-coded since it is a categorical variable as follows: Spasticity level measured by MAS scoring as Grade 1 (G1) category was used as a baseline reference category in the model in comparison with Grade 1 + (G1 +) and Grade 2(G2) categories. Spasticity level measured by MAS as Grade 1 +(G1+) category was coded as follows: [1 = G 1 +,

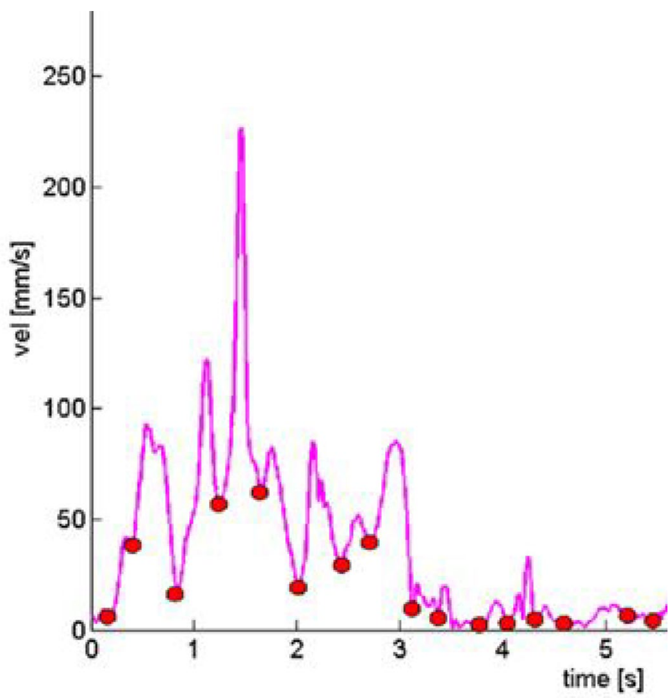



**Fig. 5**. velocity profile of wrist marker with NMU identified (red dots).

| Kinematic parameters | Mean ± SD |
|---|---|
| MT(s) | 4.05 ± 0.62 |
| PV (mm/s) | 455.44 ± 44.9 |
| PTPV (%) | 38% ± 0.05 |
| NMU | 6.40 ± 1.52 |
| NJS | 80.42 ± 6.34 |

**Table 2**. Mean ± SD of the kinematic parameters for the study participants (n = 50). SD: standard deviation; MT, movement time; PV: peak velocity; PTPV: percent time to peak velocity. NMU: number of movement units; NJS: normalized jerk score.

| Kinematic parameters | r-value | *P* value |
|---|---|---|
| Movement time | 0.651 | 0.009** |
| Peak velocity | − 0.766 | 0.001** |
| Percent time to peak velocity | − 0.649 | 0.007** |
| Number of movement units | 0.870 | 0.001** |
| Normalized Jerk score | 0.877 | 0.001** |

**Table 3**. Correlation between the level of spasticity measured by MAS and different studied parameters in the study group (n = 50). **Correlation is significant at the 0.01 level (2-tailed). *P:* probability value; r-value: spearman rank correlation coefficient value.

0 = otherwise]; and Spasticity level of Grade 2 (G2) category was coded as follows: [1 = G2, 0 = otherwise]. $R^2$ is the measure of the effect size for the model and the Statistical significance level was set at ($P < 0.05$).

## Results

Kinematic spatiotemporal parameters were computed and listed in Table 2. There were no missing data in this study as shown in the study flow chart.

### Correlation between the spasticity level and the spatiotemporal parameters

Correlation between the level of spasticity measured by MAS and the spatiotemporal kinematic parameters is displayed in Table 3.

Our results revealed a significant correlation between MAS and kinematic parameters. Normalized jerk score (NJS), number of movement units (NMU) and peak velocity (PV) were strongly correlated to MAS (r = 0.870–0.877). Peak velocity (PV) and percent time to peak velocity (PTPV) showed a negative correlation with MAS (r = − 0.64 to − 0.76) as illustrated in Table 3 and displayed in Fig. 6.

### Regression analysis between the level of spasticity and the spatiotemporal parameters

Regression analysis results between the level of spasticity measured by MAS and the spatiotemporal kinematic parameters were displayed in Table 4 and Fig. 7 as follows:

Movement time (MT): The regression model was statistically significant, $F(2, 47) = 263.55$, $p < 0.001$, indicating that the independent variable (level of spasticity) explained a significant proportion of the variance in MT with a high accuracy level of 91% ($R^2 = 0.918$). The results reveal that MT is significantly predicted by the level of spasticity ($p < 0.001$) as shown in Table 4.

Based upon the current study results, we can predict the MT according to the following regression equation as an example [all the data are displayed on Table 4][37]:

$$Y = b_0 + b_1 (x_1) + b_2 (x_2)$$

where.

$B_0$: represents the intercept (mean score of MT for the reference category (G1) on MAS.

$B_1$: represents the difference in scores for G1 + category compared to the reference category.

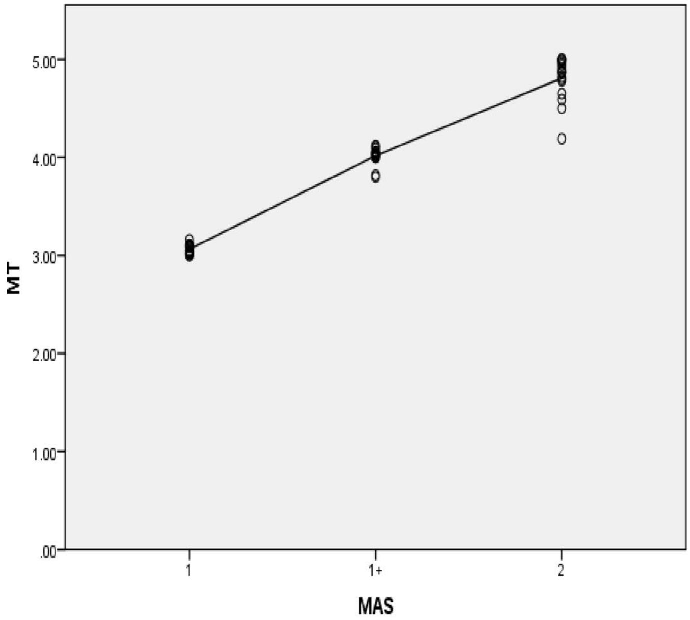
$B_2$: represents the difference in scores for G2 category compared to the reference category.

So the predicted MT during forward reaching for children with HCP with spasticity level of G1 + for elbow flexors

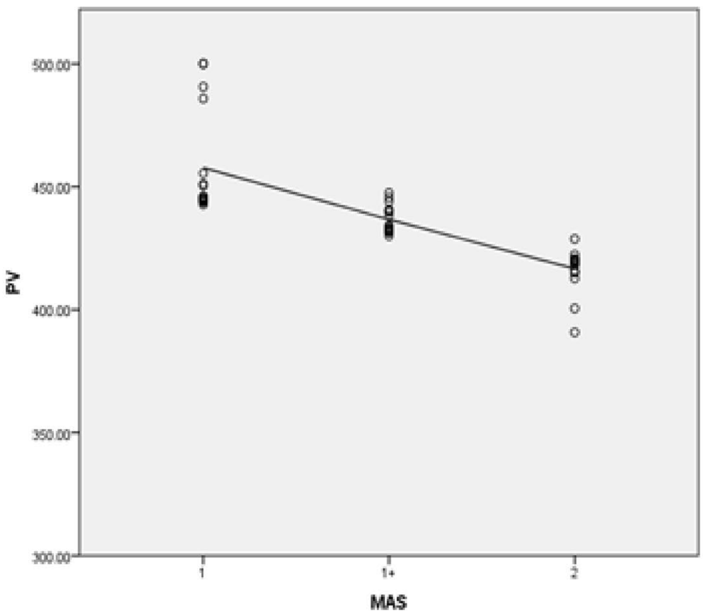
$$MT = 3.063 + 0.954 (1) + 1.783 (0) = 4.017 \text{ sec}$$

Peak Velocity (PV): The regression model was statistically significant, $F(2, 47) = 116.849$, $p < 0.001$.the regression analysis revealed that the level of spasticity accounted for 83.3% of the variance in peak velocity ($R^2 = 0.833$). The results reveal that PV is significantly predicted by the level of spasticity ($p < 0.001$) as shown in Table 4.

Percent time to peak velocity (PTPV): The regression model was statistically significant, $F(2, 47) = 1433.346$, $p < 0.001$, indicating that the level of spasticity explained a significant proportion of the variance in PTPV




(a)




(b)

**Fig. 6**. scatter plot for correlation between the level of spasticity (MAS) and the movement time [ $MT_{sec}$] (**a**); peak Velocity [$PV_{mm/sec}$] (**b**); Percent time to peak velocity [PTPV] (**c**); number of movement units [NMU] (**d**) and Normalisd jerk score [NJS] (**e**).

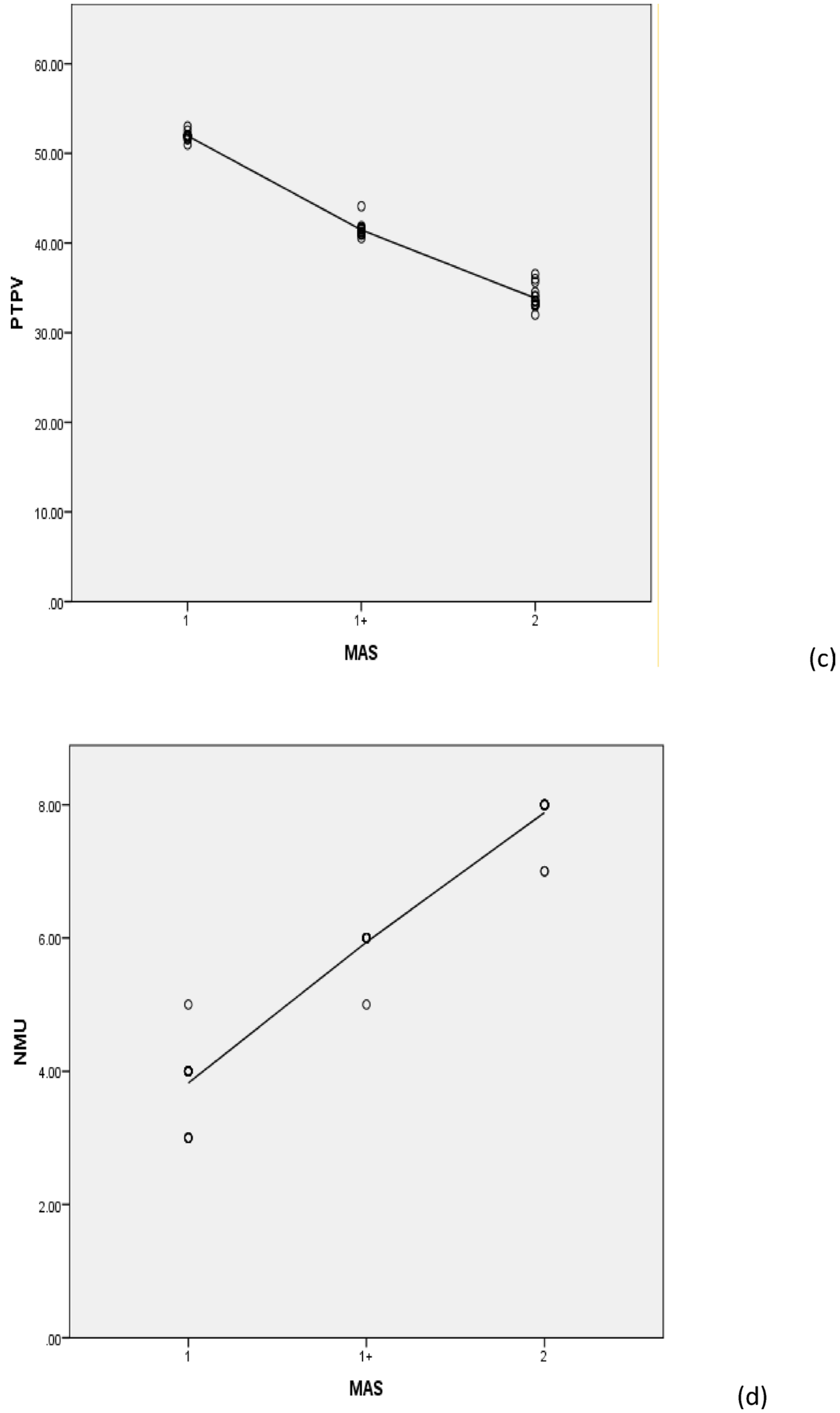
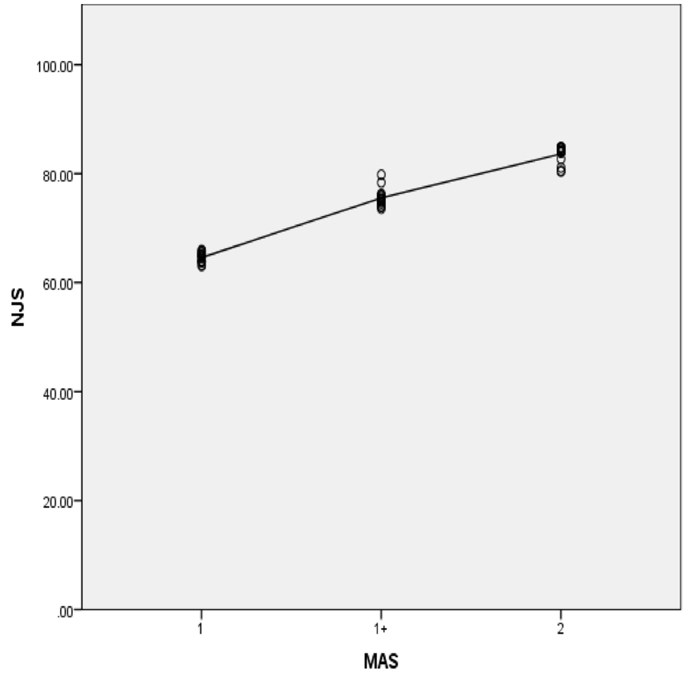



**Fig. 6.** (continued)

($R^2 = 0.90$). The results reveal that PTPV is significantly predicted by the level of spasticity ($p < 0.001$) as shown in Table 4.

Number of movement units (NMU): The regression model was statistically significant, $F(2, 47) = 1706.601$, $p < 0.001$. The level of spasticity accounted for 95.3% of the variance for NMU ($R^2 = 0.953$) indicating that NMU was highly predicted by the level of spasticity.

Normalized Jerk Score (NJS): NJS was best captured by the regression model which was statistically significant, $F(2, 47) = 401.787$, $p < 0.001$. The results revealed that 97.2% of the variation in NJS is predicted by the level of spasticity ($R^2 = 0.972$) as shown in Table 4.

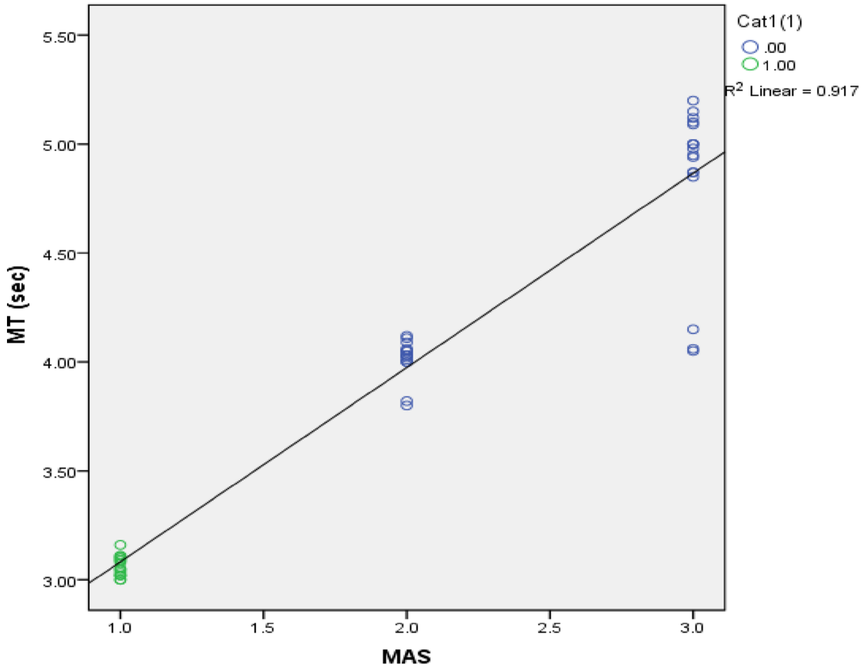



(e)

**Fig. 6.** (continued)

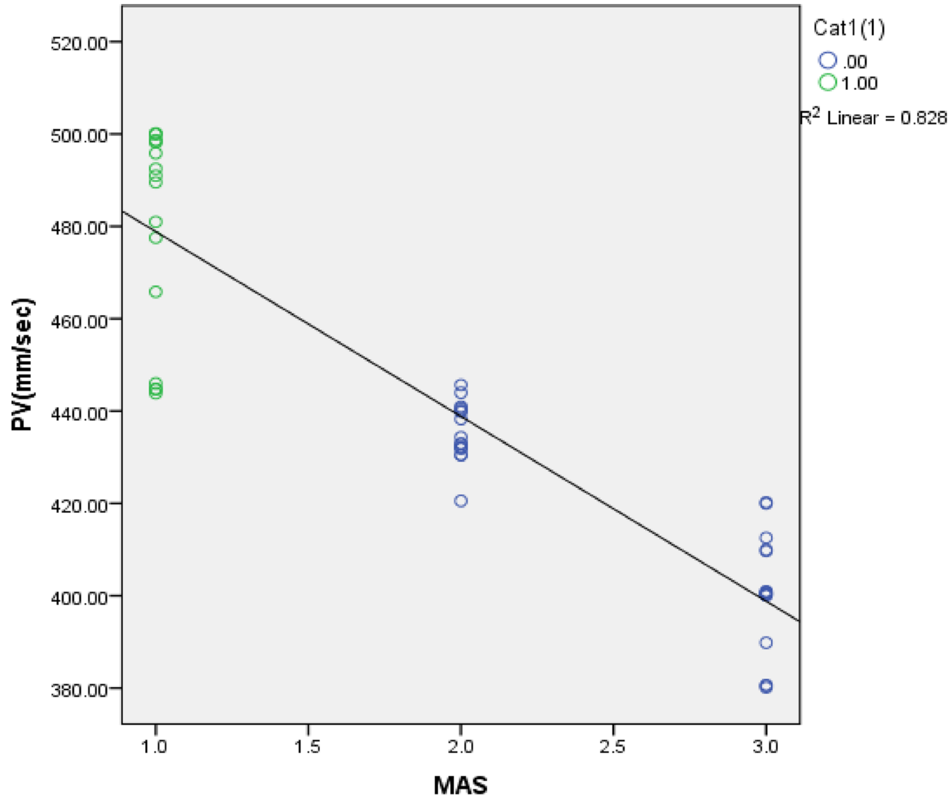
| | | | | | | | | | 95% CI | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | B | Std-error | Beta | F | Sig | t | Sig | LB | UB | $R^2$ | Adjusted R |
| $MT_{sec}$ | Constant | 3.063 | 0.055 | – | 263.55 | .000 | 55.744 | .000 | 2.952 | 3.173 | 0.918 | 0.915 |
| | G1 + | 0.954 | 0.079 | 0.580 | | | 12.087 | .000 | 0.795 | 1.113 | | |
| | G2 | 1.783 | 0.078 | 1.100 | | | 22.941 | .000 | 1.627 | 1.939 | | |
| $PV_{mm/sec}$ | Constant | 480.469 | 3.711 | – | 116.849 | .000 | 129.462 | .000 | 473.003 | 487.935 | 0.833 | 0.825 |
| | G1 + | − 45.022 | 5.330 | − 0.579 | | | − 8.447 | .000 | − 55.744 | − 34.300 | | |
| | G2 | − 80.035 | 5.249 | − 1.046 | | | − 15.249 | .000 | − 90.594 | − 69.477 | | |
| PTPV | Constant | 36.703 | 0.180 | – | 1433.346 | .000 | 204.84 | .000 | 36.342 | 37.064 | 0.896 | 0.891 |
| | G1 + | 4.561 | 0.258 | − 0.376 | | | 17.687 | .000 | 4.043 | 5.080 | | |
| | G2 | 13.382 | 0.254 | − 1.122 | | | 52.694 | .000 | 12.871 | 13.893 | | |
| NMU | Constant | 4.000 | 0.047 | – | 1706.601 | .000 | 85.113 | .000 | 3.905 | 4.095 | 0.953 | 0.952 |
| | G1 + | 2.000 | 0.67 | 0.579 | | | 29.633 | .000 | 1.864 | 2.136 | | |
| | G2 | 3.882 | 0.66 | 1.141 | | | 58.414 | .000 | 3.749 | 4.016 | | |
| NJS | Constant | 70.934 | 0.249 | – | 401.787 | .000 | 285.168 | .000 | 70.433 | 71.434 | 0.972 | 0.968 |
| | G1 + | 4.608 | 0.357 | 0.508 | | | 12.898 | .000 | 3.889 | 5.326 | | |
| | G2 | 9.963 | 0.352 | 1.116 | | | 28.322 | .000 | 9.255 | 10.671 | | |

**Table 4**. Regression analysis results for the studied variables. MT: movement time; PV: peak velocity; PTPV: percent time to peak velocity; NMU: number of movement units; NJS: normalized Jerk score; $R^2$: coefficient of determination in the regression model, F: F value of ANOVA; sig: statistical significance at ($\alpha < 0.001$); t: t value; constant: Regression constant; B: the coefficient for regression equation; std-error: the standard error of the estimate for regression model; Beta: the standardized coefficient; 95% CI: 95% confidence interval; G1 +: spasticity Grade (1 +) on MAS; G2: spasticity Grade (2) on MAS. N.B, the regression results in the table are referenced to the participants categorized as Grade (1) on MAS for spasticity level.

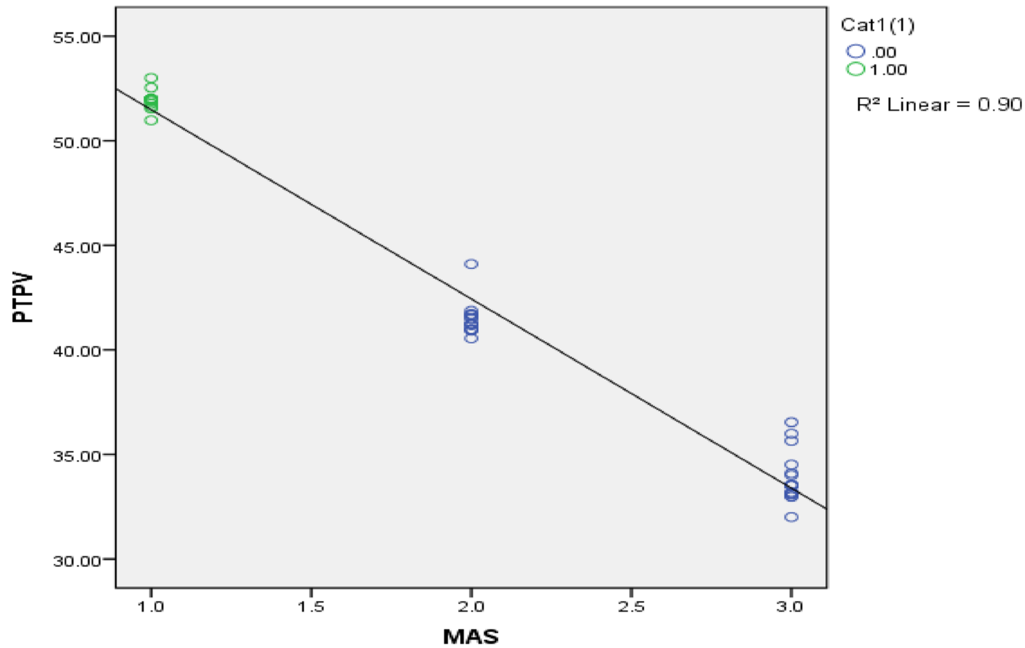



(a)

**Fig. 7**. scatter plot depicting the relationship between the level of spasticity (MAS) and the studied kinematic variables: $MT_{sec}$ (**a**); $PV_{mm/sec}$ (**b**); PTPV (**c**); NMU (**d**); and NJS (**e**). Cat 1(1): is the model baseline reference category with a spasticity level of Grade (1) MAS.




(b)




(c)

**Fig. 7.** (continued)

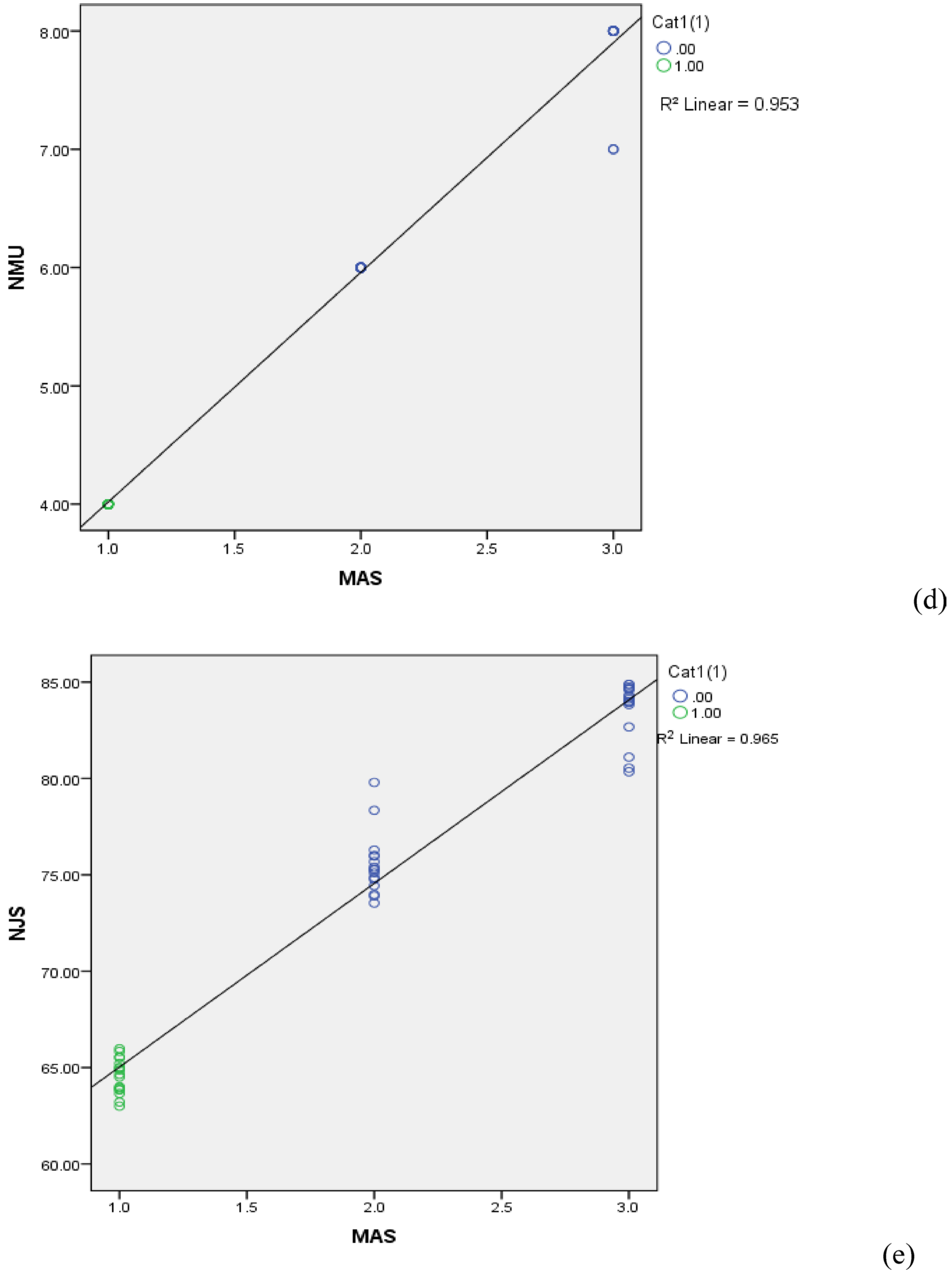



**Fig. 7.** (continued)

## Discussion

Although some previous studies had examined kinematic characteristics of reaching closely in children with hemiplegic cerebral palsy[4,32,34], there is still no consensus as to which kinematic parameters are to be preferred for the evaluation of motor performance in this population. At the same time, kinematic analysis is increasingly being used in clinical research as discriminative or evaluative measures. This reveals the need to quantify the specific kinematic parameters that provide reliable and valid information about movement characteristics.

The results of the present study indicate a significant positive correlation between movement time and the level of spasticity measured by MAS (r = 0.651).

These results were consistent with the previous study done by Chang et al.[3] who found a significant correlation between MT and MAS score in high accuracy reaching only. This also comes in agreement with the previous study done by Levin[38] who found that MT was significantly correlated to the level of spasticity in patients with stroke. So, if kinematic variables are not available in the clinical setting, MT could be used as a measure to evaluate movement in children with hemiplegic cerebral palsy.

The current study results revealed a strong negative correlation (r = − 0.766) between peak velocity and the level of spasticity measured by MAS. This indicates that subjects with higher MAS scores demonstrate lower PV amplitude during the performance of reaching. This comes in contrast with previous studies[3,39], which considered PV and PTPV as a less sensitive kinematic variable to differentiate between healthy and spastic conditions.

On the other hand, the results of the present study come in agreement with the finding of the previous study[32] which studied the spatiotemporal characteristics of reaching and grasping in hemiplegic cerebral palsy and reported movement slowness, indicating more distal movement control problems leading to increase in manual asymmetry. Others explained that lower peak velocity may be caused by many factors such as generalized muscle weakness, so, the amount of force production required for fast movement may be absent. Another reason for slowness may be to avoid an increased level of spasticity when moving fast[40].

Literature has shown that control of reaching movements needs dual-level organization. One level plans the trajectory of the movement while the other defines the interjoint coordination (movement smoothness) required for executing a goal-directed movement[16,30,33,34]. Smooth movement is thought to be the consequence of learnt inter-joint coordination, according to the previous studies on recovery from neurological disorders[41–43], therefore, for individuals with movement abnormalities due to neurological disorders, movement smoothness increases with motor recovery.

The present study results revealed very strong significant correlations among NMU, NJS and MAS (r = 0.870–0.877), indicating that participants with higher MAS scores demonstrated less smooth movement and higher NMU and NJS scores during the performance of reaching.

The movement segmentations appeared in the velocity profile of reaching movement performed by the affected hand in hemiplegic CP are due to a deficit in smooth inter-joint coordination between the elbow and shoulder joints, so, the movements appeared jerky. Another explanation is that children with hemiplegic CP need to learn how to integrate new (abnormal) proprioceptive feedback from the impaired upper extremity which leads to longer movement time due to the use of vision to redirect the hand of the impaired upper extremity toward the correct pathway leading to more segmentation in the velocity profile reflected by increased number of movement units indicating reduced movement smoothness[30,34,40].

The current study showed that NJS is the most significantly correlated kinematic variable(r = 0.877) to the level of spasticity and the most influenced parameter ($R^2 = 0.97$) by the level of spasticity as well. This comes in contrast with the previous studies[3,44] which reported that movement smoothness index (NMU) is the strongest correlated kinematic variable to the level of spasticity and it could be used to quantify the level of coordinative motor performance for subjects with spastic movement disorders and to differentiate between participants with motor deficits. These differences between the present study results and the previously mentioned studies[3,44] may be due to different sample sizes, different participant characteristics such as including different disorders (such as diplegic CP, Quadriplegic CP in addition to hemiplegic cerebral palsy) and different sampling systems.

The successful regression analysis in the current study provides a deeper understanding of how spasticity is quantitatively related to movement smoothness, as indicated by the normalized jerk score (NJS) [$R^2 = 0.97$; $p < 0.001$]. These results establish a quantitative framework to investigate the extent to which variations in spasticity levels can predict changes in the normalized jerk score during reaching tasks in children with HCP. Highlighting this relationship can help researchers and clinicians to understand the motor control deficits of forward reaching in children with HCP due to impaired motor planning, execution and feedback-related control strategy adopted in these children.

One of the strengths of the current study is providing valuable clinical implications in the field, as it might help clinicians and researchers to use NJS as an indicator to investigate the effectiveness of the established clinical interventions (such as BTX-A injection, surgery, physiotherapy,…..) and to track the progress of cases through analyzing the interference of spasticity on the motor control of reaching in children with HCP.

The limitations of the current study may include the use of a convenience sampling method, small sample size, one level of accuracy and the lack of age and gender control. These limitations would limit the generalization of our research results and precaution is needed in clinical application. Furthermore, one of the limitations is that the current study did not investigate the impact of other variables that might be associated with HCP such as stiffness, muscle weakness, presence of some dystonic features,but the selection criteria in the current study were clear and we excluded participants with such deficits. However, investigating such variables alongside spasticity should be addressed in future studies.

## Conclusion

Many possible kinematic variables can be calculated to analyze the motor performance of the upper extremity. We determined that the movement smoothness index (NJS, NMU) clearly could differentiate between typically developing children and children with hemiplegic CP. Among the studied spatiotemporal variables, NJS is mostly influenced by the level of spasticity; therefore, it could be used to evaluate more objectively the progress of recovery and the effectiveness of the treatment.

## Clinical implication

Three-dimensional Kinematic analysis of upper limb functional activities can offer significant information on numerous aspects of motor control, which might be utilized to evaluate rehabilitation strategies for children with cerebral palsy. This study confirms that the measure of movement smoothness (NJS) can be used as an important index to evaluate the effects of treatment on motor recovery and analyze the interference of spasticity on reaching control in these children, which is useful for both clinical practitioners and researchers.

## Data availability

All data are available within the submitted manuscript.

Received: 8 October 2024; Accepted: 16 June 2025
Published online: 16 October 2025

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## Author contributions

F.H., S.M., A.H., A.A., K.R., A.A., R.A., Y.S., and E.A. all participated in the research idea and its design.- F.H., S.M., A.H., A.A., K.R., A.A.,R.A., Y.S and E.A., contributed to the statistical analysis. - F.H, E.A, A.H, S.M., participated in data collection and supervision.- F.H., S.M., A. H., A. A., K.R.,A. A., R. A., Y.S, and E.A. contributed to interpreting the results and wrote the drafts of the manuscript. All authors have read and agreed to the published version of the manuscript.

## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

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