Positive and Negative Motor Signs of Head Motion in Cerebral Palsy: Assessment of Impairment and Task Performance.

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***Abstract*—This paper analyzes the presence of positive and negative motor signs in people with cerebral palsy (CP). Positive motor signs are those that lead to involuntarily increased frequency or magnitude of muscle activity. Negative motor signs describe insufficient muscle activity or insufficient control of muscle activity. In this work a head-mounted alternative computer interface based on inertial technology was used to assess motor signs in seven users with CP. Task performance and control of posture was related to the impairment. There are no significant differences between users with CP and healthy control participants in the frequency domain of the head movement. Results suggest that these kind of motor disorders are not related to positive motor signs. Moreover, a control mode based on posture more than on movements is not optimum; an alternative control mode must be specially designed for users with poor postural control.**

***Index Terms*—Cerebral palsy, motor disorder, head, inertial, human-computer interface.**

I. Introduction

CEREBRAL palsy (CP) is one of the most severe disabilities in childhood and makes heavy demands on health, educational, and social services as well as on families and children themselves. The most widely and cited definition of CP states that it is 'a disorder of movement and posture due to a defect or lesion of the immature brain' [1]. The complete definition also affirms that 'for practical purposes it is usual to exclude from CP those disorders of posture and movement which are (1) of short duration, (2) due to progressive disease or (3) due solely to mental deficiency' although most authors only cite the first brief sentence. The prevalence of CP is internationally 1.5-2.8 cases per 1000 births. Only in the United States 0.5 million infants are affected by CP [2]. In Europe these figures are even higher; the overall rate for the period from 1980 to 1990 was 2.08 per 1000 live births [3]. The work 'Surveillance of cerebral palsy in Europe: a collaboration of cerebral palsy surveys and registers' presented a consensus that was reached on a definition of CP, description and classification in terms of nosology, topography and function (severity). The nosological classification divides CP into three types: spastic, ataxic and dyskinetic. Spastic CP is characterized by at least two of these signs: abnormal pattern of posture and/or movement, increased tone and pathological reflexes. It may be either bilateral or unilateral. Ataxic CP is characterized by both abnormal pattern of posture and/or movement and loss of orderly muscular coordination; movements are performed with abnormal force, rhythm and accuracy. Dyskinetic CP is dominated by both abnormal pattern of posture and/or movement; and involuntary, uncontrolled, recurring, occasionally stereotyped movements [4].

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A. *Positive and negative motor signs*

Children with motor disorders often have a combination of multiple symptoms and clinical signs that contribute to their disability. One general classification of motor signs distinguishes two basic categories: positive signs and negative signs [5]. Positive motor signs can be defined as those that lead to involuntarily increased frequency or magnitude of muscle activity, movement, or movement patterns. Examples include hypertonia, chorea, tics, and tremor. Low frequency involuntary movements such as athetosis are not related to positive motor signs. Negative motor signs describe insufficient muscle activity or insufficient control of muscle activity. Examples include weakness, impaired selective motor control, ataxia, and apraxia [6]. Positive motor signs are often easier to detect in the clinic, and there has been significant effort to identify and quantify such signs. Negative motor signs are often more difficult to quantify, and there are fewer effective treatments. Positive and negative motor signs are often simultaneously present and may be linked rather than independent features of a motor disorder [7].

These definitions are useful in order to facilitate the development of rating scales to assess improvement or deterioration with time [7]. Furthermore, efficiency of physical, cognitive and functional therapies can be improved if they adapt to the specific needs of the users.

B. *Aim of the work*

The initial hypothesis for this paper is that negative motor signs are predominant in people affected by CP. It has been said that positive motor signs can be described by increments

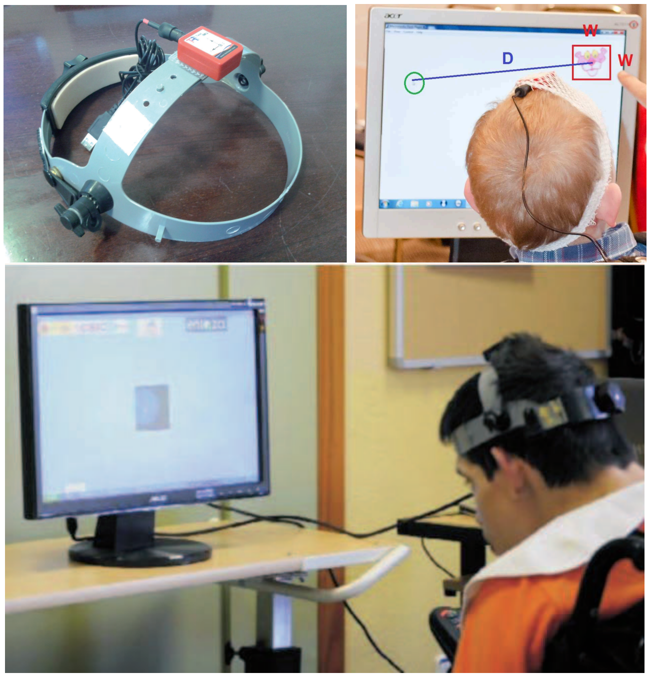

Fig. 1. ENLAZA interface: IMU and software. On the upper left corner, IMU attached to the helmet; on the right and below, participants from the cerebral palsy group during one of the work sessions. The target is a squared figure with size WxW pixels located at a distance D from the cursor.

in the frequency of muscle activity. That means that frequency components well above the dominant frequency of voluntary movements (1-2Hz) will be found in involuntary movements if positive motor signs are identified (e.g. tremor is characterized by frequencies around 5-7Hz). Head motion in users with CP and healthy subjects (HS) will be analyzed in the frequency domain. No significant difference between groups might be an indicator of the absence of positive motor signs responsible for motor disorders.

On the contrary, we expect to find significant differences in the performance of the task and head range of motion as a direct consequence of the motor and postural disorder, described by negative motor signs.

II. Methodology

The methodology is based on a reaching task. Eye and face tracking interfaces are powerful pointing devices for people with motor disorders and a very natural form of pointing as people tend to look at the object they wish to interact with. However, severe disability caused by CP requires a different approach to reduce the effect of involuntary movements on human-machine interaction. Users wore a hat or helmet with an inertial sensor attached to it (see Fig. 1). This alternative interface, called ENLAZA, allowed them to control the cursor of the computer with movements of their heads. Users were instructed to locate the mouse pointer over a static target as quickly as possible. All participants had experience with the interface so just a short training for this particular task was needed. Each work session consisted of reaching 17 targets on the screen, one for practicing and 16 for assessment. The difficulty of the task, that depended on the distance and size of the targets, was the same for all users. Two values of distance and target size were chosen; the target was located at a distance of 300 or 500 pixels from the position of the cursor. Target's size was 100x100 or 200x200 pixels large. Hence, there were 4 combinations of target size and distance. In a session, the user had to perform four repetitions in a randomized order of those four distance-size combinations, for a total of 16. Screen resolution was 1366x768 pixels.

A. Participants

Eleven subjects participated in the study (age 31.8+/-9.2). Prior to the beginning of the tests, they had completed 21+/-7 sessions in two months. Three of the participants left the study after a small number of sessions. Two of them had very poor motor control and presented difficulties to complete the task. Both continued using ENLAZA in less challenging activities. The third one was firstly included in the study but he was dropped out because he did not fully understand the proposed task due to his intellectual disability. Another participant had good performance but was not able to complete some of the sessions in time. Their tests are not included in the analysis. For the control group, 3 volunteers participated in the experiments (age 30+/-2.5). They completed 3+/-1 training sessions before starting the study. Tests took place at ASPACE Cantabria (Santander, Spain), a center specialized in CP and similar disorders. The control group or healthy subjects participated in the tests at the Bioengineering Group of the Spanish National Research Council (Madrid, Spain). Table I depicts user classification. Some other descriptors considered relevant for the study can be observed in Table II.

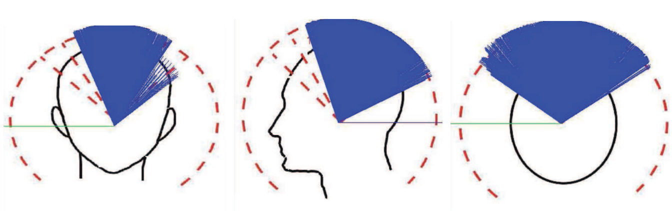

Fig. 2. Representation of the head orientation in the frontal, sagittal and transverse planes for one user with CP. Recordings correspond to a total of 16 reaching tasks with the ENLAZA interface. The Euler angles displayed are, from left to right, α, β and γ.

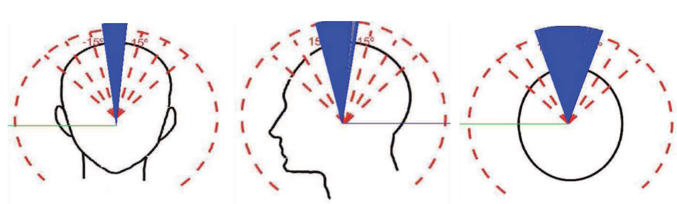

Fig. 3. Representation of the head orientation in the frontal, sagittal and transverse planes for a healthy subject. Recordings correspond to a total of 16 reaching tasks with the ENLAZA interface. The Euler angles displayed are, from left to right, α, β and γ.

B. Inertial interface and assessment software

The inertial interface consists of a headset with a cap and an inertial measurement unit, IMU. The IMU was developed in the Bioengineering Group of the Spanish National Research Council in collaboration with Technaid Ltd. It integrates a three-axis gyroscope, an accelerometer and a magnetometer. It uses Coriolis force principle to measure angular velocity and Hooke's law for acceleration. The magnetometer measures Earth's magnetic field. The IMU design is based on MEMS technology and is available in a small package (27x35x13 mm, 27 grams). It is able to measure +/- 2.0 Gauss, +/-3 g and $+/-500°/s$ in the three axes. The angular resolution of the device is $0.05°$, a static accuracy less than one degree and a dynamic accuracy of about $2°$ RMS.

IMU orientation is estimated based on the data recorded by the accelerometer, gyroscope and magnetometer. The three Euler angles α, β and γ (in the frontal, sagittal and transverse planes) are calculated from the rotation matrix:

$$\boldsymbol{R_{GS}} = \boldsymbol{R_S} \cdot (\boldsymbol{R_G})^{-1} \tag{1}$$

$$\left.\begin{array}{l} \alpha = atan\Big(-\frac{\boldsymbol{R_{GS(2,3)}}}{\boldsymbol{R_{GS(3,3)}}}\Big) \\ \beta = asin\big(\boldsymbol{R_{GS(1,3)}}\big) \\ \gamma = atan\Big(-\frac{\boldsymbol{R_{GS(1,2)}}}{\boldsymbol{R_{GS(1,1)}}}\Big) \end{array}\right\} \tag{2}$$

where $\boldsymbol{R_G}$ is defined as the rotation matrix of the global reference system corresponding to the neutral position of the head (looking at the center of the screen) and $\boldsymbol{R_S}$ as the rotation matrix that describes the orientation of the sensor at each frame.

For the purpose of this study, the mouse pointer is controlled with an Absolute system, meaning that there is a unique relationship between head orientation and location of the pointer and that after a calibration process all pixels in the screen are reachable for the user's head Range of Motion, *ROM*. During the calibration, a therapist adjusts the gain of the transfer function that translates the orientation of the head into a location of the pointer on the screen. The software captures data used to assess:

1) *Impairment.* The device captures kinematic parameters such as acceleration, angular velocity or *ROM*, which is correlated with normal and abnormal patterns (physical impairment).
2) *Performance in the task.* The application captures the positions of the mouse pointer and target during the session.

C. Assessment of impairment

Two metrics for the quantification of positive and negative motor signs were proposed in previous studies: frequency of movement and *ROM* of user's head [8], [23]. *ROM* is defined as the difference between the maximum and minimum Euler angles measured in one of the anatomical planes: frontal, sagittal or transverse (Euler angles α, β and γ). The presence of positive motor signs in the involuntary movements of users can be assessed by analyzing the frequency of those movements. Thus, the Power Spectrum Estimation, PSD, of the signals recorded by the gyroscopes in the three axes will be calculated. Posture disorders, related to negative motor signs, can be studied by analyzing the *ROM* for the three planes: frontal, sagittal and transverse. Fig. 2 and Fig. 3 depict the three angles measured in one user of each study group.

The presence of positive or negative motor signs has implications for the design of the inertial interface. If positive motor signs (increased frequency) are identified and involuntary movements are related to higher spectral components, those frequencies could be digitally filtered. On the contrary, if negative motor signs (related to poor postural control) are detected, a different approach based on movement rather than orientation is needed.

D. Assessment of task performance

In addition to the analysis of impairment, we propose two parameters for the assessment of task performance. *Throughput*, defined by the standard 'ISO 9241-Part 9. Requirements for non-keyboard input devices', is a parameter used to measure the performance in a reaching task. It is based on the time needed by the user to complete the task but also takes into account the difficulty of the proposed task and somehow normalizes the time estimation. Thus, *Throughput* is considered a more robust parameter than reaching time itself. The difficulty of the task is quantified by the index of difficulty, *ID*, which is based on the size of the target, *W*, and the initial distance from the mouse pointer to the target, *D*, see Fig. 1.

TABLE I
USER NOSOLOGICAL, TOPOGRAPHICAL AND FUNCTIONAL CAPACITY CLASSIFICATION.

User	Nosology	Topography	Function
CP1	Spastic	Quadriplegia	Severe
CP2	Dystonic-Athetoid	Quadriplegia	Severe
CP3	Dystonic-Athetoid	Quadriplegia	Severe
CP4	Dyskinetic	Quadriplegia	Severe
CP5	Dyskinetic	Quadriplegia	Severe
CP6	Spastic	Quadriplegia	Severe
CP7	Mixed	Diplegia	Severe

TABLE II
USER DESCRIPTION: RELEVANT CHARACTERISTICS.

User	Tone	Associated Movements	Intellectual ability
CP1	Hypertonia	No movements associated	Normal
CP2	Hypertonia	Athetoid movements	Normal
CP3	Dystonia	Ballistic movements	Normal
CP4	Hypotonia	Dystonic movements	Normal
CP5	Hypotonia	No movements associated	Mild intellectual disability
CP6	Hypertonia	Athetoid movements	Medium intellectual disability
CP7	Hypotonia	No movements associated	Medium intellectual disability

TABLE III
DISTRIBUTION OF PARAMETERS.

Parameter	25th Q.		Median		75th Q.	
	CP	HS	CP	HS	CP	HS
$Throughput$	0.28	2.06	0.57	2.44	0.91	3.01
ROM_{ratio_x}	1.49	0.96	2.24	1.01	3.70	1.22
ROM_{ratio_y}	1.80	0.95	3.08	1.06	5.73	1.50
DF_x	0.49	1.52	0.58	1.77	1.40	2.27
DF_y	0.45	0.84	0.54	1.26	1.66	1.54
DF_z	0.58	0.98	0.68	0.98	1.46	1.27
$75\%\ Freq_x$	1.57	2.38	2.03	3.47	2.40	3.81
$75\%\ Freq_y$	1.10	1.90	1.60	2.26	2.26	2.41
$75\%\ Freq_z$	1.85	1.56	2.34	1.66	2.73	1.95

ID can be calculated as:

$$ID = log_2\left(\frac{D}{W} + 1\right) \tag{3}$$

The *Throughput* during a single task is defined as the division between the *ID* and the reaching time and its units are bits per second [9], [14]. It is widely accepted as a tool for the quantitative evaluation of pointing devices for general population [15]-[18] and people with spinal cord injury [19], [20] or cerebral palsy [21]-[23]. Authors in those studies presented values of *Throughput* in healthy users of 2.24+/-0.88 bits/s for alternative pointing devices while the *Throughput* for traditional computer mice is usually around 3.5-4.5 bits/s.

Besides the identification of postural disorders, *Range of Motion* can be used for the analysis of task performance. Measured range of motion, ROM_M, is defined as the *ROM* calculated during a reaching task. A required range of motion, ROM_R, could be estimated based on the distance between the mouse pointer and the target at the beginning of the task and the transfer function for head-pointer movement (degrees needed to move the pointer one pixel in the screen). Ratio of *ROMs*, ROM_{ratio}, is defined as the division of ROM_M and ROM_R and can be a descriptor of how precise user's movements are:

$$ROM_{ratio} = \frac{ROM_M}{ROM_R} \tag{4}$$

The alternative interface allows users to choose whether they control the mouse pointer in the horizontal plane with head movements in transverse or frontal plane (defined as 'normal' or 'lateral' control). The maximum *ROM* reachable by the head is larger in the transverse plane than in the frontal plane, hence absolute values of *ROM* cannot be compared unless all users work with the same type of control. The new ratio of *ROMs* presented in this study is independent of the chosen type of control because differences between controls are reflected in the value of ROM_R. A value of ROM_{ratio} close to the unit would mean that the movement is efficient, therefore no overreaching was detected in the reaching task and the user did not need several sub-movements but a single movement in order to complete the task. We expect to measure higher values of ROM_{ratio} in users with CP as a consequence of poor control of motion and posture.

E. Comparison of parameters for CP and control groups

A Lilliefors normality test was run for the nine calculated parameters. Results concluded ($p < 0.05$) that the hypothesis of normality could be rejected in a number of them. Thus, a parametric test could not be used for the comparison of the populations. A non-parametric method was used instead.

The Wilcoxon signed-rank test was used to assess whether the measured parameters for the control and the CP group differed. Our hypothesis is that the *Throughput* and the ratio of *ROM* would be significantly different for the two groups. On the other hand, the presence of negative motor signs would be reflected in none statistical differences between the frequencies measured for the healthy volunteers and the subjects with CP. The null hypothesis H_0 is rejected with $p < 0.05$ and states that both populations are equal in terms of median.

III. RESULTS

The performance during the task was higher in the control group. Median values of the *Throughput* were 0.57 bits/s and

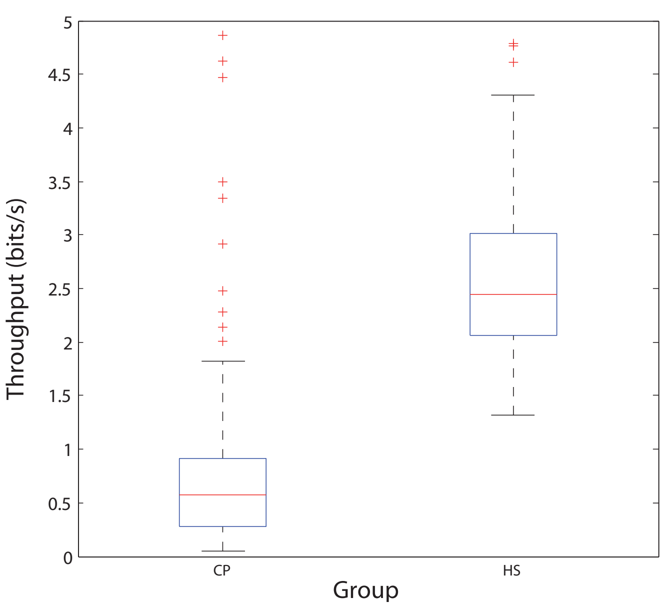

Fig. 4. Measure of *Throughput* for the two groups. The box plots represent the values measured for each task during the work sessions of cerebral palsy (CP) and healthy subjects (HS).

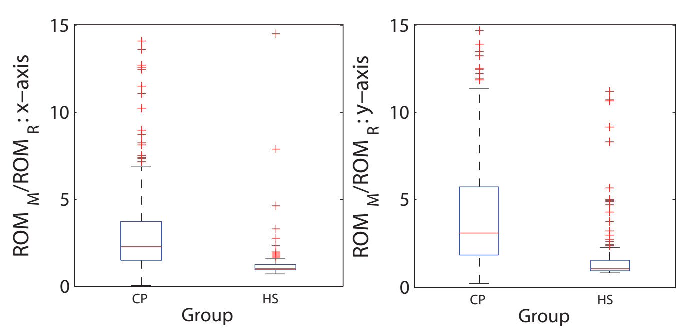

Fig. 5. Box plots representing *Measured ROM* vs *Required ROM* for the two groups: cerebral palsy (CP) and healthy subjects (HS). On the left, the x-axis; on the right, the y-axis.

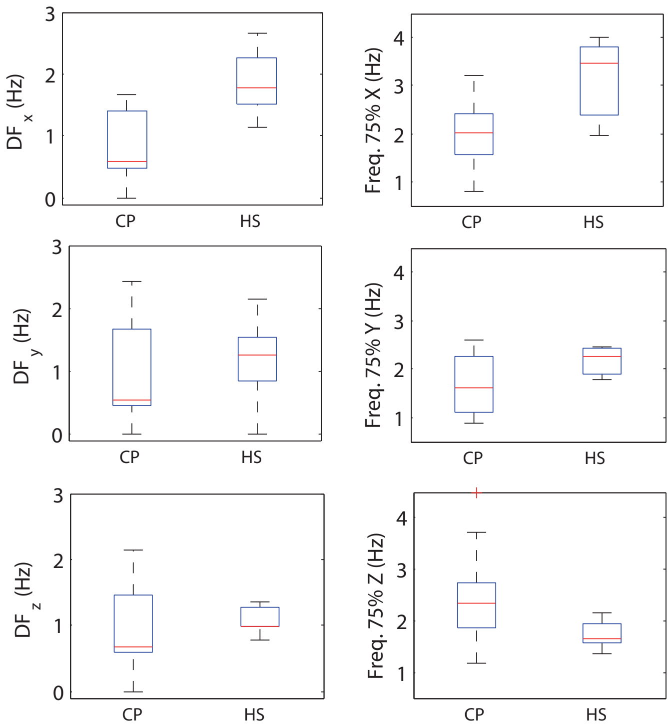

Fig. 6. In the first row, dominant frequency (*DF*) for both groups in the 3 rotations: roll, pitch and yaw. In the second row, the bandwidth at 75% of the total energy of the signal.

2.44 bits/s in the CP and control groups. Differences in the interquartile ranges, *IQR*, were smaller: 0.63 and 0.95 bits/s for CP and HS groups due to the existing homogeneity of performance within the groups (Fig. 4). The ratio of ROM_M and ROM_R is represented in Fig. 5. As expected, it was very close to the unit in healthy subjects. Medians calculated were 1.01 and 1.06 in the x and y axis, respectively. In people with CP, those values were 2.22 and 3.08. This increase (38%) in the measured *ROM* in the y-axis is consistent with the poorer postural control in the frontal and sagittal planes identified in users with cervical hypotonia. The *IQR* for both axes is around 7 to 8 times larger in the CP group, due to the heterogeneity of the user's tone and control of posture. The frequency analysis of the head motion in both groups displayed very low frequency components in the range between 0.5 and 2.5 Hz. 75% of the spectral components were below 3.5 Hz as shown in Fig. 6. Increased frequency cannot be observed in the recorded movements.

The 25^{th} and 75^{th} quartiles as well as the median value of *Throughput* (bits/s), ROM_{ratio}, dominant frequency and bandwidth (Hz) calculated for the two population groups can be found in Table III.

The statistical analysis determined that not all the measured parameters fitted a normal distribution (see Table IV). The lowest p-values estimated in the Lilliefors test corresponded to the parameters used to quantify task performance: *Throughput* and ratio of *ROMs*. That lead to the use of a non-parametric test for the comparison of medians such as the Wilcoxon signed rank test. The null hypothesis, H_0, in this test, is that the median difference between pairs of observations is zero. Statistical differences were found in the *Throughput* and *ROM* ratios for vertical and horizontal motion of the cursor. No significant differences were found in the frequency parameters. Thus, H_0 can only be rejected ($p < 0.05$) for *Throughput*, ROM_{ratio_x} and ROM_{ratio_y}.

IV. Conclusion

There are some inherent limitations to the population under study and the experiment itself that must be taken into account in order to analyze the results. The disability of the sample in the CP group is rather heterogeneous in terms of tone, involuntary movement and intellectual ability. To gather a larger CP group would be desirable for more robust statistical significance. In addition to this, some aspects such as motivation or fatigue were not quantified although they may play an important role in the performance of the task.

The statistical analysis showed significant differences in parameters of task performance between the control group and the CP group. *Throughput* was significantly lower in people with cerebral palsy while the ratio of measured versus required range of motion was substantially higher in the CP group. These are the consequences of the poorer postural control of users with cerebral palsy and the resulting lower performance in the reaching task.

The frequency analysis, however, produced different results. The median comparison test could not reject the null hypothesis although some tendencies can be observed in Fig. 6. Given the earlier enumerated limitations, statistical analysis showed no significant differences between the movements of

TABLE IV
Results of the Lilliefors normality test.

	CP		HS	
Parameter	H	p-value	H	p-value
$Throughput$	1	<**0.01**	1	**0.02**
ROM_{ratio_x}	1	<**0.01**	1	<**0.01**
ROM_{ratio_y}	1	<**0.01**	1	<**0.01**
DF_x	1	**0.02**	0	0.50
DF_y	1	<**0.01**	0	0.50
DF_z	1	**0.01**	1	**0.03**
75% $Freq_x$	0	0.50	0	0.23
75% $Freq_y$	0	0.31	0	0.28
75% $Freq_z$	1	**0.01**	0	0.19

TABLE V
Results of the Wilcoxon signed rank test. Differences between groups.

Parameter	H	p-value
$Throughput$	1	<**0.01**
ROM_{ratio_x}	1	<**0.01**
ROM_{ratio_y}	1	<**0.01**
DF_x	0	0.25
DF_y	0	0.12
DF_z	0	0.62
75% $Freq_x$	0	0.75
75% $Freq_y$	0	0.50
75% $Freq_z$	0	0.12

the CP and control groups in the frequency domain. The absence of increased frequency and the presence of increased *ROM* (due mostly to muscle weakness) are consistent with the predominance of negative motor signs.

Results also suggest that absolute control might not be the optimum control mode because it is based on posture more than on movements. An alternative is the relative control. It is based on the angular velocity measured by the gyroscopes. Its main advantage for users with decreased tone is that even if the user is leaning forward or backward due to muscle weakness, he or she will still be able to move the mouse pointer with small head movements.

In future studies, relative control will be tested in users with cervical hypotonia and will be compared to absolute control in terms of performance. Preliminary results in ongoing experiments seem to indicate that relative control is indeed a better choice for these users, but a larger sample is needed in order to confirm the hypothesis.

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