Characterizing head motor disorders to create novel interfaces for people with cerebral palsy

Creating an alternative communication channel by head motion

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Abstract—This paper aims to validate a head mounted inertial interface to characterize disorder movements in people with cerebral palsy (CP). The kinematic patterns extracted from this study will be used to design an alternative communication channel (using head motion) adapted to user’s capabilities and limitations. Four people with CP participated (GMFCS level V) and three healthy subjects as reference group. The main outcome measures were divided into 1) Time-domain, 2) Frequency-domain and 3) Spatial domain. Results showed that the inertial interface succeeds assessing the pathological motion. Firstly, the system differentiates between voluntary and involuntary motion in terms of motor control, frequency and range of motion. Secondly some motion disorders such as hypertonia, hypotonia can be identified. These results suggest that people with motor disorders could benefit from the developed inertial system in three fields: 1) diagnosis of motor disorder by means of an objective quantification, 2) physical and cognitive rehabilitation by means of proprioceptive enhancement through visual-motor feedback and 3) functional compensation by means of an inertial person-machine interface for controlling computer and assistive devices (e.g. wheelchairs or walkers).

Keywords: Human motion analysis, human-machine interaction, inertial sensors, motor disorders.

I. INTRODUCTION

A. Definition, terminology and classification of CP

Cerebral palsy (CP) is the most common motor disability in childhood and it involves a disorder of movement, posture and motor function. It is caused by a no progressive interference, lesion, or abnormality in the immature, developing brain. CP involves a group of disorders that is permanent but not unchanging [1]. The prevalence of CP is internationally 1.5–2.0 cases per 1000 births. Only in the United States 500,000 infants are affected by CP [2]. In Europe these figures are even higher, [3].

CP is an umbrella term which involves a wide variety of diseases. It can be classified according to the pathology of brain injury or according to the timing of brain injury. The Reference and Training Manual of the Surveillance of Cerebral Palsy in Europe (SCPÉ) divides CP into three groupings based on the predominant neuromotor abnormality – spastic, dyskinetic or ataxic, with dyskinesia further differentiated into dystonia and choreoathetosis, [4]. The changing nature of symptoms and signs makes the clinical classification difficult in the first years of life as the pattern of movement and tone may change completely.

Spastic CP is the most common form. Spastic CP cases have increased tone and pathological reflexes. Increased tone in spasticity is characterized by an increased resistance which is velocity dependent. A spastic catch is felt some time after onset of movement. Dyskinetic CP cases present involuntary, uncontrolled, recurring, and occasionally stereotyped movements. The primitive reflex patterns predominate, and the muscle tone is varying. Dystonic CP is dominated by abnormal postures and hypertonia. Characteristics are involuntary movements, distorted voluntary movements. Choreo-athetotic CP is dominated by: hyperkinesias and hypotonia. Chorea means rapid involuntary, jerky, often fragmented movements. Athetosis means slower, constantly changing, writhing, or contorting movements. Ataxic CP cases present loss of orderly muscular coordination, so that movements are performed with abnormal force, rhythm, and accuracy. Abnormal pattern of movement in ataxic CP is characterized by: (1) Loss of orderly muscular coordination, (2) Tremor (mainly a slow intention tremor), (3) Low tone is also a prominent feature.

The head may be affected by any of the five basic types of dyskinesia: tremor, tic, chorea, myoclonus, and dystonia, [5,6]. In addition, the head is subject to two dyskinesias which we call "flopping" and "nodding." Head tremor is an active, wholly involuntary, sustained pendular oscillation. Myoclonus may be "Jerk" which consists of rapid contractions or "Rhythmic" when affecting the head, closely resembles tremor. Flopping is a passive, involuntary movement characterized by transient, exponentially decaying occurring at the end of active head movement. Tic and nodding are acquired behavioural patterns. A tic is a single, rapid, stereotyped movement. Nodding is an active, regular, sustained, usually pendular oscillation.

B. Instruments to assess motor function in CP

When assessing people with CP, many factors must be taken into consideration and the symptoms need to be monitored by an interdisciplinary team. In the literature,
different instruments used in pediatric rehabilitation and pediatric physical therapy to assess the functional motor abilities of people with CP can be found.

The WHO International Classification of Functioning, Disability and Health (ICF) along with several other recent publications, have sensitized health professionals to the importance of evaluating the functional consequences of different health states. For ambulation, the Gross Motor Function Classification System (GMFCS) has been widely employed internationally to group individuals with CP into one of five levels based on functional mobility or activity limitation.

Most methods are subjective measures that classify the motor involvement on the basis of functional abilities. In milder cases, the assessment and conclusions may vary by the subjective examinations of various professionals. Therefore, a combination of significant motor developmental delay and abnormalities in the neurologic examination is required to determine the diagnosis. Magnetic resonance imaging (MRI) is a preferred method of diagnosing. This technique can be very helpful in determining if the child has brain damage, which could lead to cerebral palsy. Another promising approach is the use of normal and abnormal general movement patterns. This method appears to have high sensitivity and specificity for the diagnosis of CP, [7, 8]. Motion sensing, by means of MEMS inertial sensors is a real scientific breakthrough in the medical field, where there is a need for small ambulatory sensor systems for measuring the kinematics of body segments, [9]. Inertial sensors enable ambulatory biomechanical measurements. As a result, inertial sensors have been chosen for different applications focused on people with CP, such as the evaluation of clinical spasticity assessment (by measuring the range of motion), [10], the quantification of standing balance by assessing displacement of the center of mass, [11] and clinical assessment of tremor [12].

This paper aims to quantify the motor disorders of people with CP by using a new head-mounted inertial interface. This system tracks the user’s head movements and translates them into the displacements of the mouse pointer on the screen. Although all areas of the motor function can be limited, limbs are usually more affected than the head motion in infants with severe CP, [13] This is the reason why the inertial interface presented is a head mounted device.

II. METHODOLOGY

A. Apparatus: the inertial interface

The interface is based on an Inertial Measurement Unit (IMU) that integrates a tridimensional (3D) accelerometer, a 3D gyroscope and a 3D magnetometer mounted on a commercial helmet. A calibrated IMU measures 3D acceleration (caused by motion and gravity), 3D angular velocity and 3D earth magnetic field. Orientation of the IMU can be estimated by a data fusion algorithm presented by [14].

At the onset of each trial, a calibration must be performed to estimate the head orientation respect to the computer screen and measure the angular ranges of motion (ROM). Fig. 1 depicts the inertial system. The transverse and sagittal rotations are translated to horizontal and vertical displacements of the pointer respectively. The frontal rotation does not produce displacements. The inertial tracker sampled at 50 Hz with a maximum error of 1.34°, or about 17 pixels (with a resolution of 1024 pixels). The inertial interface was technically validated by five healthy users (aged 25-32 years) following the standard ISO-9241 Part 11, [14].

![Inertial interface. Trials in ASPACE- Cantabria](image)

**TABLE I. CP PARTICIPANTS CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Cervical Tone</th>
<th>General Tone</th>
<th>Associated Movements</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP1</td>
<td>Extensor hypertonia</td>
<td>Extensor hypertonia</td>
<td>Atetosis</td>
</tr>
<tr>
<td>CP2</td>
<td>Dystonia</td>
<td>Dystonia</td>
<td>Ballistic</td>
</tr>
<tr>
<td>CP3</td>
<td>Hypotonia</td>
<td>Hypotonia</td>
<td>No</td>
</tr>
<tr>
<td>CP4</td>
<td>Hypotonia</td>
<td>Dystonic</td>
<td>Dystonic</td>
</tr>
</tbody>
</table>

B. Participants

4 people with severe CP were recruited (Table I). Their mean age was 29 years (range: 26-35). They cannot control mouse pointer or keyboard. 3 healthy users participated to extract the normalized patterns for comparison. Tests with CP people were carried out in ASPACE-Cantabria (Santander, Spain). ASPACE-Cantabria has expertise in using some alternative devices as eye-tracking interfaces. Vrije Universiteit Medisch Centrum (VUMC, Amsterdam, The Netherlands) collaborated on the settings of the software application. VUMC has expertise in designing specific software for children with CP. Tests with healthy users were carried out in Bioengineering Lab – CSIC (Madrid, Spain).

C. Procedure

The trial required participants to look at an on-screen target and dwell on it for selection. Then, the target changed its position following a sequential order. Participants were instructed to locate the cursor over the target as quickly as possible using head motion. There were 5 sessions during a week using an inertial pointing device. The kinematic data were recorded during the trial. The experiment consisted of reaching the target 15 times. This trial was repeated during 5 days once per day. Therefore the target-reaching task was carried out 75 times in total. The target-reaching task is attractive because it provides a statistical description of the involuntary movements made during voluntary activity.

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D. Main outcome measures

The metrics described in this section are introduced in order to quantify the motor disorder.

1) Time-domain analysis. Motor disorders can be evidenced by muscle tone variations causing lack of coordination. Fitt’s law is a complete metric which models human psychomotor behaviour based on Shannon's Theorem, [15]. It is specifically described for target-reaching tasks. It is assumed to be a reliable estimation of goal motor coordination. The human psicomotor behaviour is simulated as an electronic channel for the information transmission measured in bits/s. A signal is transmitted through a non-ideal medium and is perturbed by noise. The effect of the noise is to reduce the information capacity of the channel. Fitts’ law proposes the logarithm-linear relationship between the amplitude of the movement, the target width and the average movement time. The R-Square ($R^2$) will measure the correlation between the model and the data.

2) Frequency-domain analysis. A frequency-domain analysis is necessary because motor disorders (e.g. tremor [11]) are frequency and time-varying. Fast-Fourier transform (FFT)-based spectral analysis and the time-varying spectral density (spectrogram, PSD) are analyzed. Components calculated from spectral density curves are (1) frequency at peak amplitude density and (2) three-fourths total amplitude frequency. A low-pass filter at a cutoff frequency of 10Hz was introduced to reduce the influence of electrical noise on the measurement.

3) Spatial-domain analysis. Abnormal postures can be identified by measuring the spatial variables such as the predominant head orientation and the range of motion (ROM). Neck/head motion is clinically described as rotations about 3 orthogonal axes imbedded in the head. Euler Angles are useful for describing human motion such as head movement because they define rotation using three angles that can easily be physically related to frontal, sagittal, and transverse ($\alpha$, $\beta$, $\gamma$) axes. Defining $R_S$ as the orientation of the global reference system corresponding to the neutral position of the head (looking at the screen during calibration) and $R_t$ the orientation at each frame, the angles are calculated as:

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

$$\alpha = \text{atan}(-R_{GS(2,3)} / R_{GS(3,3)})$$

$$\beta = \text{asin}(R_{GS(1,3)})$$

$$\gamma = \text{atan}(-R_{GS(1,2)} / R_{GS(1,1)})$$

ROM is defined as the difference between the maximum and minimum values of $\alpha$, $\beta$ and $\gamma$. $\beta$ and $\gamma$ are related to the vertical and horizontal total range which is defined by calibration. The result is the ratio of the total range. Therefore, if the ROM ratio is less than 1, the subject moved his/her head between the screen limits; otherwise the head was out of range. $\alpha$ is given as absolute value because frontal rotation does not produce pointer displacements.

III. RESULTS

A. Healthy subjects (H1, H2, H3)

Fig. 2 illustrates the pointer and target coordinates (horizontal ‘x’ and vertical ‘y’) versus time where a characteristic voluntary motion is represented. Fitts’ law describes the human psychomotor behavior as showed by frequency-domain analysis. Fig. 3 depicts the correlation between Fitts’ law and the motor control for a healthy user. The natural behaviour performing a reaching task can be modeled by (1) an initial movement that rapidly covers distance and (2) a slower homing-in phase. This voluntary movement describes a logarithmic law between amplitude of the movement and the time in order to maintain the trade-off between speed and accuracy. The motion can be composed by several “sub-movements” especially to home on the target. These “sub-movements” are usually performed with lower velocity and correspond to the trajectory correction. Table II illustrates the $R^2$ correlation between the Fitts’ model and the psicomotor behavior. This analysis shows that the correlation is about an 83% for healthy subjects.

The frequency-domain analysis showed that the predominant component was of low frequency for all subjects (frequency at peak amplitude density was about 0.3Hz, called ‘voluntary frequency’, see Table III). As an indicator of the spread of the frequency components, the frequency at which 75% of the spectral area was below, or three-quarters of total amplitude frequency, ranged between 1.5Hz and 3.5 Hz with a mean about 2Hz. This result has been found to be in agreement with the literature [6] where it is recognized to be the natural frequency for a healthy person. The spectrogram (fig. 4) shows the spectral density with time. Black and red colors are used for high energy, yellow for medium energy, light blue for low energy, and dark blue for very low energy. The maximum spectral density (black areas) reaches up to 2Hz which corresponds to the target transitions.

ROM ratio for sagittal and transverse rotations was less than 1 (Table IV). It means that the head rotations were performed between the range limits defined by calibration. The average value for the frontal rotation was about eight degrees which is also considered to be a sign of motor coordination. Graphical results can be observed in fig. 5. Notice that the angular motion is balanced for clockwise and anti-clockwise directions. This fact is another sign of motor control and ability to maintain the head in the desired position.

B. Subjects with Cerebral Palsy (CP1, CP2, CP3, CP4)

1) Subject CP1. Fig. 6 illustrates the pointer and target coordinates (horizontal ‘x’ and vertical ‘y’) versus time. Voluntary movements are evidenced because pointer follows the movements of the target. This fact demonstrates that a
component at voluntary frequency (about 0.3Hz) exists. However, pathological movements and postures also exist complicating the task performance.

Cervical tone was classified as extensor hypertonia which may be appreciated by an excessive tone of the muscles which is more pronounced in extensor than flexor muscles.

**Figure 2. Dynamic evolution of the pointer and target (Healthy subject)**

Fig. 6 (blue line) shows repetitive fluctuations. According to the FFT these fluctuations are the result of a combined motion. The frequency of these fluctuations was about 1Hz (peak amplitude) and caused by the athetotic movements. They were not detected during complete rest.

**Figure 6. Dynamic evolution of the pointer and target (CP1)**

Combined to these movements there are irregular movements which are represented by a continuous power spectrum which decreases with increasing frequency reaching a value about 3Hz (75% of spectral energy, Table III) about all axes. These results were found to be in agreement with the literature [16]. As can be seen in the spectrogram (fig. 7) the frequency of the involuntary motion in an individual athetotic patient may vary over a wide range (0.4-5Hz). This result is
dissimilar to rest tremor of Parkinson’s disease where the frequency of tremor is relatively constant in any one patient in the range of 3-7Hz [17]. Analysis of ROM (Table IV) showed a wide motion in frontal, sagittal and transverse rotations. Regarding Fitts’ Law analysis, voluntary speed modulation appears combined with quick involuntary accelerations which modify the voluntary control law. As a result, the number of sub-movements is greater than that of healthy users and the main movement towards the target is often composed of more sub-movements. Nevertheless, voluntary motor control appears eventually modulating the motor behavior following a logarithmic law which demonstrates the voluntary actions superimposed to involuntary components (R²=32%, Table II).

2) Subject CP2. Similar to CP1, voluntary movements are evidenced because the pointer follows the target. It is also showed that involuntary movements are superimposed to the voluntary actions. Dystonia causes jerky movements with irregular amplitudes and variable frequency as showed in the spectrogram analysis. The frequency bandwidth was ranged between ‘voluntary frequency’ (<0.5Hz) up to 3-5Hz (75% of spectral energy) summarized in Table III. The frequency at peak amplitude density was about 0.3-0.6Hz which is slightly higher than the frequency of a healthy subject. These jerky movements were not detected during complete rest. However, abnormal posture may appear during rest because the head drops forward (caused by low muscle tone).

This case is similar to subject CP1 respect to hypertonic movements (frequencies range). However it can be observed that the fluctuations caused by dystonia are particularly variable in amplitude and frequency. Dystonia causes that the predominant frequency may be similar to the healthy frequency but that eventually it may be affected by hypertonic movement. From the spatial-analysis domain arises that frontal rotation is higher than that of healthy subject and CP1. However, sagittal and transverse are considerably balanced. According to sagittal range, CP2 is able to control the head in erect position. This fact implies that hypotonic episodes do not appear regularly. These hypotonic episodes can be seen in CP3. Regarding to Fitts’ Law analysis, although jerky movements are presented, residual motor control can be observed (R²=50%, Table II).

3) Subject CP3. Hypotonia is a decreased muscle tone which causes that the head drops forward. Sagittal ROM is meaningfully different respect to the other subjects, as can be observed in fig. 8 and Table IV. Notice that the unbalanced sagittal rotation is clearly wider respect to frontal and transverse. It might be explained because the pull of gravity makes difficult to hold his head up. It suggests differences in coordination and control in the hypotonic group due to postural abnormalities more than involuntary movement at high frequency (as hypertonic cases). Arising from these results, floppy dyskinesia was identified. In a healthy subject the tendency for the head to resonate is well controlled by damping due to neck muscle tone and by control signals which correct for external disturbances (ROM rate <1 for healthy subjects). However, when muscle tone is reduced (hypotonia), the head/neck system becomes underdamped and tends to oscillate both at the termination of voluntary movement and when head posture is passively disturbed by other body movements [6]. The maximum density spectral at these events is about 2Hz. Frequency-domain analysis showed similar result respect to normal patterns. Peak amplitude was slightly lower (0.17-0.38Hz) than ‘voluntary frequency’. Hypotonia involves reduced muscle strength which might affect motion speed. The frequency bandwidth was ranged between <0.5Hz up to 2.5Hz (75% of spectral energy, Table III). Despite of involuntary motion the R² correlation was relatively high (R²=62%, Table II) implicating motor control exists.

4) Subject CP4. The rest pose of subject CP4 is characterized with the head falling to the left side caused by hypotonia. Consequently, the lateral rotation conditioned the range of movements. ROM analysis showed wide unbalanced ranges. Moreover, dystonia causes quick movements from the neutral position to an unstable posture to reach the target. Although, the target can be followed, it is expected to improve using a head-support to assist the decreased head control. The frequency at peak amplitude density was about 0.3-0.6Hz.
which is slightly higher than the frequency of a healthy subject. This result is similar to CP2 case due to the common dystonic movements. The frequency bandwidth was ranged between 0.5Hz up to 3-5Hz (Table III).

IV. DISCUSSION AND CONCLUSION

Abnormal head movements and postures were studied in four subjects with CP using an objective recording technique and the data analyzed with respect to metrics. These parameters quantitatively described the differences between healthy and affected subjects and allowed the objective assessment of the motor disorders.

The predominant voluntary frequency is 0.2-0.4Hz for healthy users. Nevertheless, the frequency reaches up to 2Hz at the target transitions when speed is increased following the human motor behaviour defined by Fitts’ Law ($R^2=83\%$). The ROM rate was less than 1 meaning that the ROM was maintained in of range. The ROMs were balanced what implies motor control and coordination.

The similarities between subjects with motor disorders seem to be related to the mechanisms normally responsible for the fine control of voluntary head movement and for stabilization of the head during disturbance of posture. Time-domain analysis demonstrated that gross motor function is not as affected as fine motor control because all subjects could follow the target on the computer screen completing the task in a relatively short time. That means all subjects have a natural or voluntary frequency. Subjects with hyper tonia and dystonia were more sensitive to accuracy requirements (fine motor function) than people with hypotonia who were more sensitive to certain postural requirements (gross motor function).

Due to limited continuous control of ROM and poor motor coordination, subjects with CP may have difficulties in planning and executing precise movements. Numerous submovements appear constantly which complicate the fine control. Nevertheless, some phases which follows Fitts’ Law can be recognized and seems like a subject can improve these results by training.

Inertial technology leads to improvements in the objective quantitative assessment of movement disorders. The findings of this study are in agreement with some studies in the literature demonstrating the inertial system provides a basis for classification of abnormal head movements and postures. The device will result useful for: 1) diagnosis of motor disorder by means of an objective quantification, 2) physical and cognitive rehabilitation by means of visual-motor feedback and 3) communication facilitating the person-computer interaction.

Future work will be focused on evaluating the impact of motor learning with long-term studies especially at the early ages because of the brain plasticity. Different filtering techniques will be analyzed in order to reduce the effect of the involuntary motion on the control of the device. These findings suggest that adaptive filters are necessary in order to be adjusted to different spatial and kinematic parameters. The inertial interface will intend to be an alternative/augmentative channel of communication between people with severe motor diseases and computer or assistive devices.

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