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On the performance assessment during the practice of an exergame for cerebellar ataxia patients

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***Abstract*— Cerebellar ataxias are a large family of movement disorders that generally follow a stroke. The clinical picture is very complicated and normal activities become difficult for ataxic patients. For instance, dynamic ataxia involves both walk and upper-limbs movement, thus affecting the possibility to fulfill daily life tasks. Rehabilitation treatments and strategies for cerebellar ataxia are nowadays controversial, since different opinions on the several approaches are spread among the clinical community. The purpose of the present work is not to shed some light on such disagreements. Indeed, here a solution for delivering rehabilitation activities in the form of videogame is presented. Data related to patient's performance are collected and analyzed in order to provide the clinical staff with objective indicators that properly describe the activity. Such information can also be used to discuss the effectiveness and the incidence of some strategy adopted for fulfilling some task. The experimental phase is conducted on two case-studies with regards to the upper-limb rehabilitation. The adoption of the strategy of weighting the limb when performing the movement is discussed. The indicators computed in both sessions with and without strategy are compared, also referring to the practice of some healthy subjects. The present work introduces the preliminary phase of a wider study and foretells its future development conducted on a larger population.**

***Index Terms*— assessment, cerebellar ataxia, upper-limb.**

I. INTRODUCTION

Prior the spread of the Covid-19 pandemic, stroke was usually referred to as the 21^{st} *Century epidemic* by the medical community. Stroke is indeed the second leading cause of death worldwide, and also the second most common cause of disability-adjusted life years (DALYs) [1]. Many people experiencing a stroke are left permanently disabled, placing a burden on family and society. It is then clear that stroke is an important sanitary emergency and, therefore, also the need for rehabilitation has become a very crucial issue.

In such a context, cerebellar stroke accounts for approximately 2% to 3% of all strokes. Acute cerebellar stoke manifests itself with axial and or limb ataxia, nystagmus, vertigo, action tremor and dysarthria. The cerebellum works as a motor feedback control system: it compares the motor command elaborated in premotor areas with sensory-motor inputs, and then produces an error signal. A cerebellar damage can impair its ability to sufficiently integrate sensory input in order to monitor and correct movements.

By practicing some activity while tracking patients' movements, their conditions can be assessed taking into consideration whether a strategy is being adopted or not. To this end, a combination of an information and communications technology (ICT) support and classical rehabilitation is the starting point of this study. In order to foster patients' rehabilitation and enhance their engagement, the activities are delivered in the form of exergames [2]. Exergames is an umbrella term referring to a category of video games which combine virtual support with physical exercise. Exergames can be adapted to several clinical conditions, giving the possibility to modulate neuronal plasticity, encouraging learning and recovery, and practicing task-oriented training. Even though the role of traditional therapy and clinicians is irreplaceable, exergames can be an accessible and challenging support to classical rehabilitation to encourage patients to continue treatments in time. For instance, studies [3], [4] propose a stroke rehabilitation program to develop a system to support the ambulatory rehabilitation therapy based on motor learning principles and theories in rehabilitation. In addition, aerobic exercise was proved to have a crucial role in poststroke therapies, in order to enhance brain function [5]. Eventually, immediate feedback turns out to be highly important, as it determines an instantaneous motor control to adjust the movement, thus promoting motor learning and neural plasticity [6].

There are lots of solutions which focus on upper-limbs exergames rehabilitation, such as [7]–[11]. In this work, the ReMoVES platform was used [12].

The aim of the present work is to quantitatively evaluate the performance during the practice of an exergame for stimulating the upper-limb movement. Hence, peculiar features of movement, such as dynamic range of motion (ROM) of different articulations of the arm (shoulder, elbow) and the inclination of the trunk, are defined and computed. On the basis of such quantitative features, one can easily perform a data analysis. Such features enable clear visualizations, allowing clinicians to easily picture patients' performance, even without directly attending them. The experimental phase is conducted on two case-studies with regards to the evaluation of upper-limbs mobility. Unfortunately, the spread

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of the Covid-19 pandemic has hindered the involvement of a wider population to the present study. The adoption of the strategy of weighting the limb when performing the movement, i.e., placing some weight on the limb being involved in the movement, is discussed. The indicators computed in both sessions with and without strategy are compared, also referring to the practice of some healthy subjects. The current manuscript presents a starting point for several possible applications: i) a support for a quantitative evaluation of therapy; ii) an easy way to remote control of training; iii) the definition of criteria for evaluating therapeutic strategy.

II. Materials and methods

In this section, the activity provided by the ReMoVES platform for cerebellar ataxia evaluation is presented, along with a brief description of the platform itself. Then, the two case-studies discussed in the following are introduced.

A. *ReMoVES and Shelf Cans activity*

The ReMoVES system is designed to support motor and cognitive recovery through exergames and digital versions of standard rehabilitation tests, carried out via Microsoft Kinect v2, Leap Motion and touchscreen. It fosters mild-intensity and continuous activity to facilitate the continuity of care even after the de-hospitalization.

Among the available activities, Shelf Cans is designed for upper-limbs reinforcement. Such exergame is set in a virtual kitchen environment, and the task is to practice real-life activities such as storing items on a shelf. In particular, the patient is required to move a colored can, which appears in the center of the screen, to the shelf containing other cans of the same color. The color of each can is aimed at stimulating a particular movement. The red, green, and orange cans require hyperadduction movement, flexion-extension movement, and a combination of both flexion-extension and abduction-adduction movements respectively. Despite the tracking provided by the Kinect is 3-dimensional,

Fig. 1: Shelf Cans print screen.

and so are data related to patient's joints positions, the game setting is 2-dimensional, as the cans can be moved on a plane parallel to the patient's coronal plane. Tracking patient's movement while practicing such an activity allow for collecting joints position at a frequency of 10 Hz. Figure 2 shows the complete list of joints provided by the Microsoft Kinect sensor.

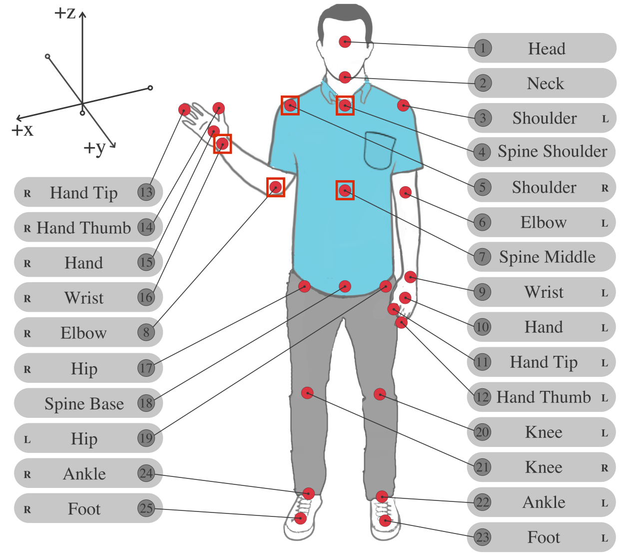


Fig. 2: Joint locations provided by the Microsoft Kinect sensor. Joints used in this work are highlighted by red boxes.

In addition, also the cans positions in the game plane are tracked, at the same frequency of 10 Hz.

B. *Patients description*

Two patients were involved in the present study. Patient A was a 49-year-old man, who suddenly experienced unsteadiness of gait, incoordinate movements of the right limbs, blurred vision and diplopia. The neurological examination showed a severe right ataxia and a bilateral gaze evoked horizontal nystagmus. Standing and gait were ataxic and broad-based. Brain MRI revealed a right cerebellar infarction. Two weeks later, the cerebellar signs improved moderately.

Patient B was a 59-year-old man who presented with sudden headache, nausea, speech disturbances and unsteadiness of standing and walking. The neurological examination revealed a moderate axial and right limb ataxia, together with slurry speech. Brain MRI showed a right cerebellar hemorrhage. After ten days, a slight improvement of the cerebellar signs and symptoms was observed.

After the acute phase of the disease, both patients were admitted to the Neurological Rehabilitation Unit of Ospedale Policlinico San Martino IRCCS of Genoa. The Scale for the Assessment and Rating of Ataxia (SARA) [13] was utilized to evaluate the severity of the cerebellar disorder. SARA values range from 0/40 (no ataxia) to 40/40 (most severe ataxia). Patient A scored 24/40 and Patient B scored 13/40. The Activity-Specific Balance Confidence Scale (ABC) [14] was also employed to assess the subjective confidence of balance (0% not safe at all, 100% completely safe). Patient A had 60%, while Patient B reported 74,3%. In conclusion, it is worth underlining that the two patients were similar in height and weight.

III. Experimental phase

A. Direct and indirect approach

Patients data have been analyzed via a direct and an indirect approach. Direct analysis employs 3D coordinates of joints provided by Kinect sensor. According to the biomechanical model, the human body can be considered as a system of rigid bodies, i.e., a set of body segments connecting the joints. Each pair of adjacent segments is considered as a kinematic and rotational pair. Consequently, significant features can be extracted to describe patient's movements. Referring to the present exergame, the analysis is focused on the upper-limb movement. The patient is required to extend the elbow and move the shoulder in order to store the can, without tilting the trunk to compensate the lack of reserve movement.

The computed indicators are the range of motion of the shoulder and elbow in the coronal plane, and the range of motion of the trunk in the sagittal plane. In particular, let us consider a fixed time, and define the shoulder and elbow angles in the coronal plane, and the trunk angle in the sagittal plane as

$$\theta_{shoulder} = \arctan \frac{z_8 - z_5}{x_8 - x_5}, \quad (1)$$

$$\theta_{elbow} = \theta_{shoulder} - \arctan \frac{z_8 - z_{16}}{x_8 - x_{16}}, \quad (2)$$

$$\theta_{trunk} = \arctan \frac{z_4 - z_7}{y_4 - y_7}, \quad (3)$$

respectively. Notice that shoulder ad elbow angles have been defined with respect to the right arm; the definition for the left arm is straightforward. Hence, the range of motion of the shoulder and elbow in the coronal plane, and the range of motion of the trunk in the sagittal plane are defined as

$$ROM(\theta_{shoulder}) = \max \theta_{shoulder} - \min \theta_{shoulder}, \quad (4)$$

$$ROM(\theta_{elbow}) = \max \theta_{elbow} - \min \theta_{elbow}, \quad (5)$$

$$ROM(\theta_{trunk}) = \max \theta_{trunk} - \min \theta_{trunk}, \quad (6)$$

respectively.

For what concerns the indirect analysis, it was performed through 2D data obtained by the videogame. The three specific tasks of Shelf Cans, referring to the differently colored cans, are split. Then, the straight line connecting starting position and targets is computed, and will be hereinafter referred to as *the optimal trajectory*. In addition, the so-called *approximate trajectory* performed by the patient during the game session is computed as the regression line of hand-game positions during the considered task. The lower the angle between the two lines, the better and controlled movement was done by the patient. Indeed, small angles shows that the approximate fitted path is similar to the optimal one. Conversely, large angles are typical of trajectories which are far from the optimal one. The linearity of scope-oriented movement is usually valued during physical therapy for patients affected by pathologies of motor learning such as cerebellar stroke. The importance of such an indirect analysis relies on the fact that it allows for quantifying the degree of improvement of the pathology which has caused the deficit of movement, and also to quantify the motor learning.

B. Case-studies application

For each patient, two sessions of Shelf Cans exergame were considered, namely with and without weighting the involved upper-limb. Indeed, according to Bhanpuri et al. [15] a cerebellar damage likely causes an inertial mismatch between an internal representation of body dynamics and the actual body dynamics. On this base, a hypometric and a hypermetric cerebellar patient would respectively underestimate or overestimate their limb's inertia. Adding mass to the affected limbs can have beneficial effect on such a mismatch. Some other authors, however, failed to replicate the beneficial effects of such a strategy, especially for multi-jointed reaching movements [16]. The patient played the exergame while sitting, in order to reduce trunk and arms oscillation in the standing position, which could negatively affect the collected data.

Here, the effect of weighting the limb is quantified in order to provide the clinical staff with such objective data. The weight amounts of one kilo, and was placed on the wrist of the used limb. The Microsoft Kinect sensor was place in front of the players, at a distance of three meters. The duration of the game session is 90 seconds. In order to avoid the influence of the order in using or not the weight for the activities, two hours time distanced the first and second session, so that they can be considered independent. In addition, some training session had been performed the days before these trials, for familiarizing with the system.

Values of the indicators extracted from both the sessions with and without the strategy are summarized in Tables I and II, and the graphs referring to the indirect analysis can be visualized in Figures 3, 4. In Figure 6 values of the ROM are depicted.

TABLE I: Angles between the approximate and optimal trajectories.

	Red can	Orange can	Green can
Pat. A no weight	7.18	63.77	13.96
Pat. A weight	6.25	5.28	2.32
Pat. B no weight	4.70	49.37	11.49
Pat. B weight	5.82	1.89	12.80

TABLE II: ROMs of shoulder, elbow and trunk.

	Shoulder ROM	Elbow ROM	Trunk ROM
Pat. A no weight	14.66	54.86	17.01
Pat. A weight	149.47	108.25	7.72
Pat. B no weight	128.56	24.54	5.47
Pat. B weight	132.03	3.76	3.39

The weighting strategy yielded a more precise movement in the performance of Patient A, which is denoted by the decreased angle between the estimated and optimal trajectories, and also by the increased range of motion of both shoulder and elbow. In addition, the reader can notice that the range of motion of the trunk decreases when patient A has a weight on the limb. This is probably due to a major control on its arm that is enabled by the strategy.

The same strategy resulted less efficient for Patient B, where, apart from the angle between the estimated and optimal trajectories when handling the orange can, no other significant better performance could be detected. In general, indicators values are better for patient B, and his better general condition is likely the reason for a less visible effect of the strategy on the performance.

Aimed at favoring comparisons with healthy subjects, a control group of six persons was considered and took part to the same treatment as patients. The values of the indicators extracted from both the sessions with and without the weight are summarized in Tables III and IV. Also, an example of graph about the indirect analysis is depicted in Figure 5. In general, it is worth noting how the adoption of the weight strategy did not yield to relevant difference for healthy subjects.

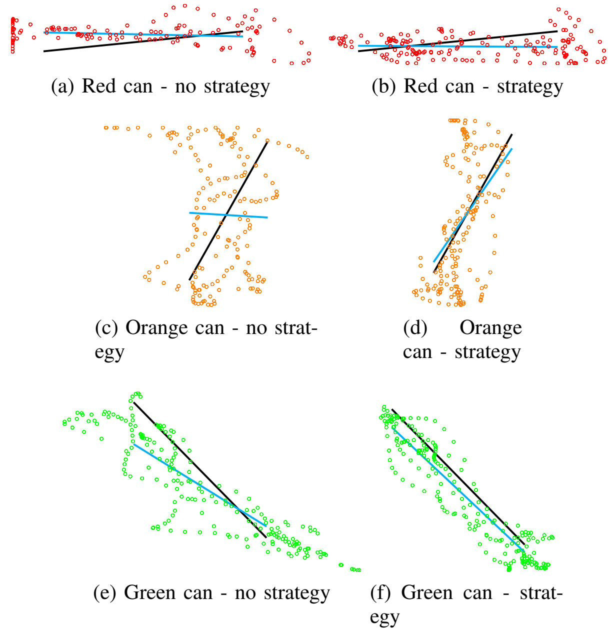
TABLE III: Angles between the approximate and optimal trajectories in the control group.

	Red can	Orange can	Green can
Sub. 1 no weight	6.29	1.75	4.55
Sub. 1 weight	5.02	2.02	5.69
Sub. 2 no weight	4.25	19.11	3.13
Sub. 2 weight	5.85	15.65	1.48
Sub. 3 no weight	4.21	28.26	1.15
Sub. 3 weight	6.57	13.29	2.69
Sub. 4 no weight	7.52	0.54	2.98
Sub. 4 weight	2.60	2.87	0.16
Sub. 5 no weight	0.42	0.35	0.92
Sub. 5 weight	1.24	1.03	0.60
Sub. 6 no weight	5.20	9.23	2.22
Sub. 6 weight	6.01	3.33	5.01
Avg. healthy no weight	4.65	9.87	2.49
Avg. healthy weight	4.55	6.37	2.61

TABLE IV: ROMs of shoulder, elbow and trunk in the control group.

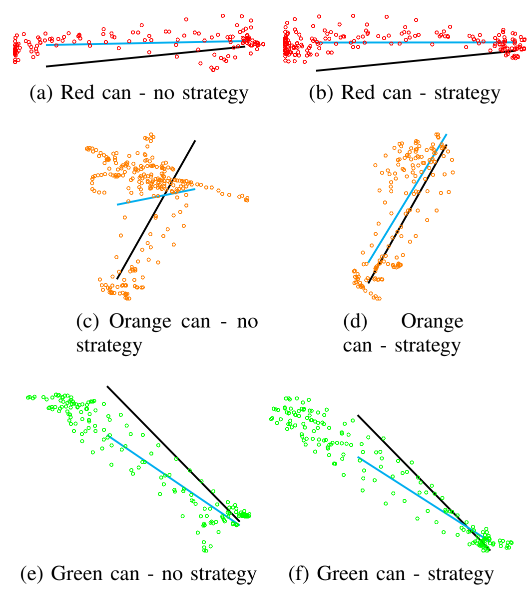
	Shoulder ROM	Elbow ROM	Trunk ROM
Sub. 1 no weight	179.71	97.76	3.68
Sub. 1 weight	179.21	140.48	4.89
Sub. 2 no weight	179.58	168.21	10.64
Sub. 2 weight	178.72	139.03	12.73
Sub. 3 no weight	179.22	72.48	5.54
Sub. 3 weight	179.74	92.56	5.23
Sub. 4 no weight	179.43	68.34	3.71
Sub. 4 weight	179.95	36.12	3.18
Sub. 5 no weight	179.49	46.30	3.75
Sub. 5 weight	178.45	45.65	3.22
Sub. 6 no weight	179.80	79.77	16.33
Sub. 6 weight	178.77	74.65	12.70
Avg. healthy no weight	179.54	88.81	7.28
Avg. healthy weight	179.14	88.08	6.99

In general, this analysis is conducted to be delivered to the clinical staff, in order to help them in defining a personalized plan of care, and also to support patients in acquiring or reacquiring faculties to employ in daily life activities.



(a) Red can - no strategy (b) Red can - strategy (c) Orange can - no strategy (d) Orange can - strategy (e) Green can - no strategy (f) Green can - strategy

Fig. 3: Patient A, approximate (light blue) and optimal (black) trajectories, and hand positions, based on the can color (dots).

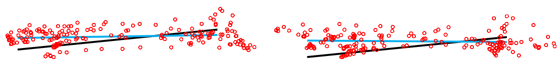


(a) Red can - no strategy (b) Red can - strategy (c) Orange can - no strategy (d) Orange can - strategy (e) Green can - no strategy (f) Green can - strategy

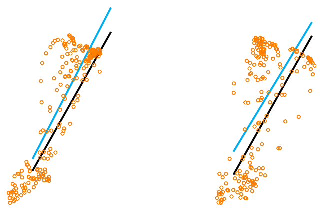
Fig. 4: Patient B, approximate (light blue) and optimal (black) trajectories, and hand positions, based on the can color (dots).

IV. Conclusion

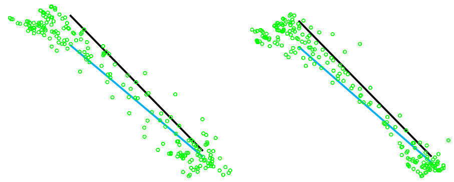
Patients suffering from cerebellar ataxia experience huge difficulties in dealing with ordinary activities, as they are not able to efficiently control their movements. A very debated strategy for fulfilling upper-limb task is to weight the arm,



(a) Red can - no strategy (b) Red can - strategy

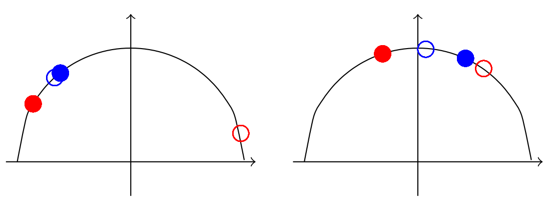


(c) Orange can - no strategy (d) Orange can - strategy

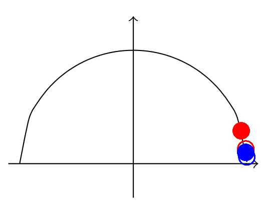


(e) Green can - no strategy (f) Green can - strategy

Fig. 5: Subject 1, approximate (light blue) and optimal (black) trajectories, and hand positions, based on the can color (dots).



(a) Shoulder ROM (b) Elbow ROM



(c) Trunk ROM

Fig. 6: Patients A and B shoulder, elbow, and trunk ROMs visualizations. Red marks refer to Patient A, blue marks refer to Patient B. Empty circles are for sessions without adopting the weighting strategy, full circles are for sessions where the weighting strategy was adopted.

aimed at improving the control capabilities. Quantifying the incidence of such a strategy may be very informative for the clinical staff following the patients, in order to define a personalized plan of care and help them in deploying daily life activities. ICT solutions may help in providing such an objective evaluation. In the present study, the ReMoVES system was used. In particular, this work is the starting point for a quantitative analysis for upper-limb performance of patients suffering from post stroke cerebellar ataxia. ReMoVES results in a solution allowing for evaluating strategies that may be adopted for the rehabilitation treatment.

Here, two case-studies have been presented. The aforementioned strategy did not have the same effect on the two patients. Therefore, such a work will be conducted on a wider population and involving many rehabilitation centers, in order to better investigate such an approach.

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