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Upper Limb Motor Skills Performance Evaluation Based on Point-and-Click Cursor Trajectory Analysis: Application in Early Multiple Sclerosis Detection

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ABSTRACT We present an enhanced version of the input device evaluation application (IDEA) system as an objective method for evaluating upper limb motor skills performance. By introducing three new metrics for mouse cursor trajectory analysis, along with the application of the two-dimensional (2D) experiment in the case of multiple sclerosis (MS), we examine the sensitivity of the IDEA system for differentiating patients with early-stage MS and healthy participants. The IDEA system calculates multiple kinematic metrics for point-and-click tasks: movement time, index of difficulty, effective target width, effective index of difficulty, throughput, missed clicks, target re-entry, task axis crossing, movement direction change, orthogonal direction change, movement variability, movement error, movement offset, mean velocity, velocity peaks, and maximum/mean velocity ratio. The results reveal that the IDEA system sensitivity has been improved in comparison with previous studies, which is high enough to detect the presence of early-stage MS with a 70.9% success rate in the 2D experiment.

INDEX TERMS Cursor trajectory, human-computer interaction, motor skills, point-and-click, user interfaces.

I. INTRODUCTION

Studies in Europe show that 0.1% of the general population is not able to use their arms, 0.3% is not capable of using their fingers, 1.4% show declined hand coordination, and 2.8% have reduced hand strength [1], [2]. Cerebral stroke, myopathy, cerebral palsy, or multiple sclerosis (MS), are among the leading causes of motor problems affecting the patients' hands. The total estimated prevalence rate of MS is 0.083% with higher rates in northern countries and a female to a male ratio of around 2.0 [3].

Over the years the need for proposing new and effective methods for assessing upper limb dexterity and skills has become very substantial. Clinical scales for measuring upper limb performance and traditional subjective tests include [4] the Expanded Disability Status Scale (EDSS) [5], Upper Extremity Index [6], Purdue pegboard [7] and the 9 Hole Peg Test [8]–[12], but their subjective character has motivated scientists to find more objective and validated ways of kinematic data acquisition. Nowadays, assistive devices and mechanical sensors have shown a significant impact in measuring upper limb dexterity as well as contributing to the domain of rehabilitation after stroke [13]–[14]. Devices used for the evaluation of patient's upper extremity, range from motor encoders, tachometers, potentiometers, electromagnetic sensors, inertial sensors [15]–[18], haptic interfaces [19] to commercial motion trackers such as Microsoft Kinect [20].

Considering the effect of the above approaches for understanding and countering upper limb movement performance, it is substantial to implement such techniques in patients with Multiple Sclerosis (MS) to provide a more comprehensive motor profile of subtle deficits. Several types of research

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that try to evaluate motor fatigue and deficiencies in patients with MS have been held using functional magnetic resonance imaging (fMRI) [21]–[23], and depth sensing cameras [24]. Also, a recent relative study [25], sought to quantify subtle changes in motor control in multiple sclerosis using a Fitts' law [26]–[29] reciprocal aiming task presented on a computer touchscreen. More specifically, the given task required participants (22 patients with MS and 22 matched controls) to draw an uninterrupted horizontal line back and forth between 2 circles with varying size and distance between them across several trials of variable difficulty. The calculated metrics were dependent to movement planning (Peak velocity, Dwell time, Time to peak), online control of movement (Time from peak, Asymmetry index) and movement error (Constant error and Variable error).

From an ergonomic perspective, studies [30]–[31] have thoroughly reviewed several published articles related to the functional capacity evaluation of the upper limb, as well as the upper extremity quantitative assessment from kinematic data. These studies classify upper extremity movements into three categories: I) Reaching Movements describe point to point moves with starting and ending locations, II) Path Drawing represents movements that require to follow a desired closed trajectory where the ending point corresponds with the starting point, and III) Activities of Daily Living refer to basic tasks that involve reaching movement, object manipulation, proximal and distal transport movements, releasing the object and return to the starting position. Consequently, a certain number of kinematic metrics have been proposed and classified into several classes according to the movement characteristics that they describe like: speed (Movement Time, Mean Velocity, Max Velocity), efficacy (Active Movement Index), efficiency (Hand Path Ratio, Index of Difficulty and Performance), accuracy (Movement Deviation, Target Error, Spatial Overshoot), smoothness (Ratio Mean and Max Velocity, Number of Peaks, Mean Arrest Period Ratio, Zero-Crossings in Acceleration Profile, Jerk, Spectral Arc-Length), control strategy (Time to Velocity Peak) and functional range of motion (Reaching Range of Motion).

In our recent study [32], we introduced the Input Device Evaluation Application (IDEA) system for the implementation of a one-dimensional pointing task experiment involving 29 MS patients and 25 healthy participants. Results showed that the IDEA system sensitivity was high enough to predict the presence of early multiple sclerosis with a 69.1% success rate. We originally developed the IDEA system along with the corresponding experiment and measurement protocols for research purposes with a primary goal to evaluate users' performance when using various computer input devices for GUI interaction [33]. IDEA supports all input devices that emulate the functionality of the mouse, i.e., that perform mouse cursor movement, positioning, and target clicking. The experiments' design followed the guidelines provided by "ISO 9241-9: Ergonomic requirements for office work with visual display terminals (VDTs) – Part 9: Requirements for non-keyboard input devices" [34], [35]. IDEA monitors, logs, and analyzes mouse cursor trajectory on the computer screen, using the pixel coordinates of the mouse cursor as raw data. Calculated trajectory measures quantify cursor movement and allow for performance evaluation [36], [37]. Furthermore, IDEA examines how Fitts' law fits the input devices under test [2], [38], [39].

Using IDEA in the field of Human-Computer Interaction (HCI) and Assistive Technology (AT), one can: a) objectively test and compare mouse emulation input devices for motor-disabled users, and select the most appropriate one, b) achieve the optimum settings of the selected input device so that the user achieves maximum performance, and c) evaluate changes in user performance over time in order to study learning effects. In the field of Biomedical Informatics, the IDEA system can contribute to: i) objectively evaluate the subject's upper limbs kinematic performance in cases of motion-related diseases and ideally detect these diseases at an early stage, ii) objectively measure the effect of a (new) drug on patients with a motoric upper limb deficit: whether and how it has improved upper limbs' kinematics, how long its effect lasts, and iii) objectively evaluate the performance of an upper limb rehabilitation program such as physiotherapy and kinesiotherapy.

Our first experimental study with IDEA aimed to measure the effectiveness of Brain-Computer Interface (BCI), and compare it with the mouse on point-and-click tasks performed by non-disabled and upper-limb motion-impaired users [40]. We concluded that Fitts' law could only describe able-bodied users' performance when selecting targets with the mouse. On the other hand, the performance of both user groups with the BCI, and of motor-impaired users with the mouse did not conform to Fitts' law. Results showed that that the BCI device could not compete with the mouse regarding performance at that time, but could be used as an alternative for motion actuated devices when no other solution was possible. Subsequently, we extended the IDEA's functionality to 3D tasks. We re-engineered the software, introduced new trajectory measures, and upgraded the UI and accuracy. In this research direction, we tested 3D pointing devices like Wiimote [41] and Kinect [42], and we found that Kinect has better performance in 3D.

The current work aims to investigate the improvement of the IDEA system's sensitivity and the augmentation of its capabilities regarding the evaluation of upper limbs' motor skills. The objective of the current research is to enhance the accuracy and validity of the IDEA system by objectively distinguishing control participants from patients with early-stage multiple sclerosis diagnosis without clinically apparent motor impairments, based on upper limb kinematics' analysis. The novelty in comparison to our previous studies [32] is the addition of a new two-dimensional experiment as well as the introduction of three new cursor trajectory parameters. All new features contribute to the evolution of the IDEA system as a reliable and effective method for assessing human motor skills through a computer-based system.

We begin with the presentation of the IDEA system, by showcasing the various kinematic parameters and their implementation and then we proceed to the explanation of the medical protocol we followed. Finally, we demonstrate the derived results, ending up with a discussion about the current study and future ones.

II. METHODOLOGY

A. THE IDEA SYSTEM

We developed the IDEA system in the Speech and Accessibility Laboratory, Department of Informatics and Telecommunications, National and Kapodistrian University of Athens, Greece. Initially, we used it as a detailed subjective user performance evaluation approach for computer input devices [40]–[43]. The system takes advantage of specific kinematic parameters, described later in this section, and offers a systematic movement analysis based on specific cursor trajectory analysis parameters. The IDEA system is capable to determine the effectiveness of any computer input device with mouse emulation, such as a trackball, or a joystick, that requires movement of the upper limb, as well as alternative control methods, such as a Brain-Computer Interface [40], or a 3D force feedback mouse [41]–[42]. In the current work, we use the traditional mouse.

Our methodology includes one-dimensional (1D) and two-dimensional (2D) point-and-click experiments for the dominant and the non-dominant hand. The user sits on a chair (with adjustable height) in front of a desk with an ergonomically defined position following ISO 9241-5 [44]. He/she places the hands on the desk, to use a standard mouse for computer input, and looks at a standard monitor at a viewing distance of 600mm; he/she avoids over-reaching for the mouse, and extension of the forearm and shoulder at all times.

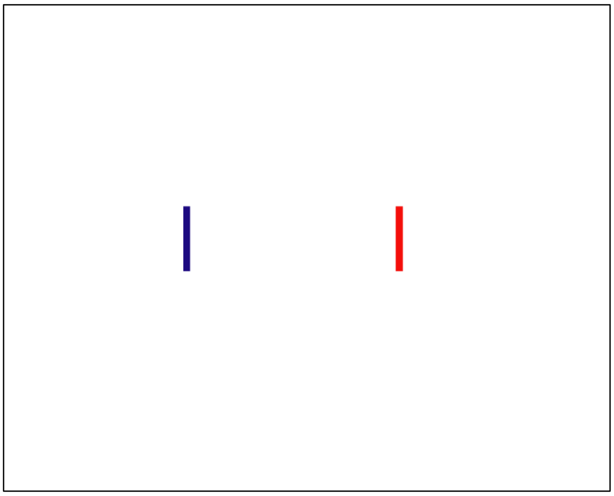

FIGURE 1. **The IDEA 1D experiment screen (for a specific session).**

In the 1D experiment (Fig. 1) two targets are graphically displayed on the computer screen, and the user is required to move the mouse cursor from the blue to the red target and click on it by pressing the left mouse button. After a successful selection (click), the starting point and the end target interchange roles, as well as their colors, so the user will make repetitive pointing and clicking tasks moving the cursor back and forth on the horizontal axis.

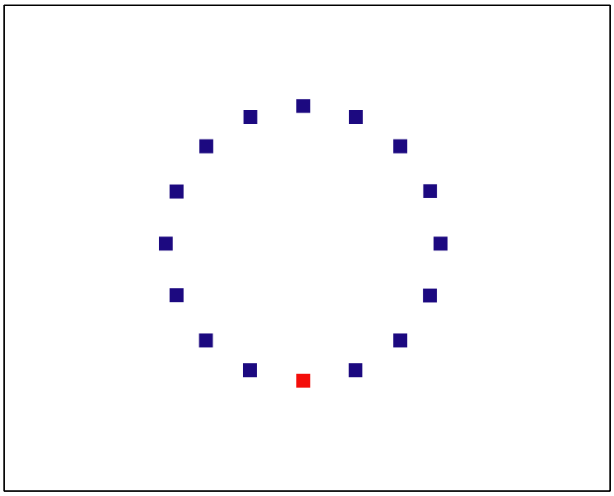

FIGURE 2. **The IDEA 2D experiment screen (for a specific session).**

In the 2D experiment (Fig. 2) sixteen targets are graphically displayed on the computer screen, and the user is required to move the mouse cursor from the top blue target (start) to the red target (end), and click on it by pressing the left mouse button. After a successful selection (click), the previously end target plays the role of the new blue target (toggles to red), and the target next (clockwise) to the previously start target plays the role of the new end red target (toggles to red), and so on, until the user selects all targets. As a result, the user accomplishes pointing and clicking tasks by moving the cursor back and forth on the vertical, horizontal, and diagonal axis in various angles.

Each of the experiments comprises sessions, each with a different Index of Difficulty (*ID*), specified by the corresponding target size and the distance between the targets. In all experiments, targets are rectangular, and each session consists of several repetitions of moves (trials). Each trial starts from the center of the start target and requires the selection of any part of the end target to complete. In the following paragraphs, we provide a detailed description of the Index of Difficulty (*ID*) as well as all the other metrics we used.

The basic configuration of the IDEA system relies on the ISO/TS 9241 - 411:2012 standard: "Ergonomics of human-system interaction - Part 411: Evaluation methods for the design of physical input devices" [45]. Besides, this ISO offers guidelines for the ergonomic design of devices such as mice, trackballs, touch screens, and light pens. It also specifies input device evaluation methods. Finally, it provides standards for human-computer interface testing, including the use of the Shannon form of Fitts's law [26]–[29], [46] (the most essential aspects of which are described thoroughly later in this chapter), instructions and layouts to design experiments that will assess the speed, convenience, accuracy and comfort with which the user performs actions such as pointing and clicking. Apart from the devices mentioned above, ISO 9241 has also been used in experiments using parts of the human body, such as the lips [47] or the head [48].

B. BASIC METRICS

Fitts [26], [27] proposed a model for the tradeoff between accuracy and speed in human motor movements, to quantify a movement task's difficulty using information theory and "bits" as the measurement unit. According to Fitts, the **Movement Time (*MT*)** needed to hit a target is linearly related to the **Index of Difficulty (*ID*)** of the task:

$$MT = a + (b \times ID) \tag{1}$$

where a and b are constants specified through linear regression, and

$$ID = \log_2(\frac{D}{W} + 1) \tag{2}$$

where D and W are the target's distance and width respectively.

Figure 3a shows a "perfect trial," the ideal line between two targets (i.e., a "perfect" trajectory), defined as Task Axis, namely the straight line joining the centers of the start target and the end target.

Fitts quantified the human rate of information processing in aimed movements using "bits per second" as units. He named the metric "Index of Performance"; today it is more commonly known as **Throughput (*TP*)**, in bits/s. Although different methods of calculating TP exist in the literature [49]–[52], the preferred method is the one proposed by Fitts in 1954 [27]. The calculation involves a division of means: dividing ID (bits) by the mean MT (seconds), computed over a block of trials for a specific session:

$$TP = ID_e/MT \tag{3}$$

The subscript e in ID_e reflects a small but important adjustment, which Fitts endorsed in a follow-up paper [53]: The "adjustment for accuracy" requires first computing the **Effective Target Width (W_e)** as:

$$W_e = 4.133 \times SD_x \tag{4}$$

where SD_x is the observed standard deviation in a participant's selection coordinates over repeated trials with a particular D-W condition. Computed as in (4), W_e includes the spatial variability, or accuracy, in responses. In practice, it captures what a user did, rather than what he/she was asked to do. The adoption of W_e requires a similar adjustment to ID, yielding an **Effective Index of Difficulty (ID_e)**:

$$ID_e = \log_2(\frac{D}{W_e} + 1) \tag{5}$$

TP constitutes a human performance metric that incorporates both the speed and accuracy of the user responses. *TP* is most suitable as a dependent variable in factorial experiments using user groups, pointing devices or pointing techniques as independent variables.

Based on the above we have adopted the following parameters proposed by McKenzie *et al.* [37].

A **Missed Click (*MC*)** occurs when the user fails to click the target but selects a point off-target instead. *MC* is a dimensionless quantity representing how many times per trial the user misses the target. The average *MC* per trial is registered when a session is complete. In a perfect trial, $MC = 0$.

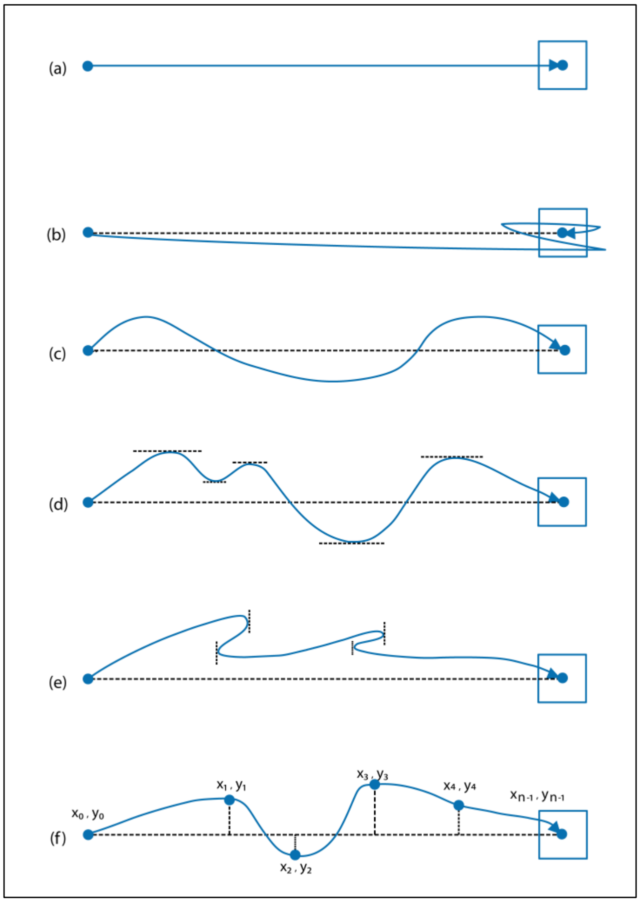

FIGURE 3. Target to target trajectory graphics for the explanation of (a) task axis, (b) target re-entry, (c) task axis crossing, (d) movement direction change, (e) orthogonal direction change and movement variability, and (f) movement variability.

A **Target Re-Entry (*TRE*)** occurs when the cursor enters the target area and exits without the user being able to click it; this happens three times in Fig. 3b. In each trial, the system counts the Target Re-Entries and registers the final number (average) of *TRE* incidents per trial at the end of the experiment. For instance, in the case of three target re-entries in a 20-trial session, *TRE* will be 0.15 for this session. In a perfect trial *TRE*= 0.

A **Task Axis Crossing (*TAC*)** occurs every time the cursor crosses the Task Axis. In Fig. 3c there are two incidents. We calculate *TAC* as an average score per trial for every session. In a perfect trial *TAC*= 0.

A **Movement Direction Change** (***MDC***) occurs when the tangent of the cursor path is parallel to the Task Axis. The following algorithm can demonstrate it: First, we calculate the difference $(y_i - y_{i+1})$ of all the (x, y) samples; i ranges from 1 to n, where n is the total number of all the (x, y) samples taken for the current trial. Then we multiply all the consecutive pairs of results $(y_i - y_{i+1})\times(y_{i+1} - y_{i+2})$. The *MDC* value is equal to the number of times a sign swap appears in the products. For example, five *MDC*s occur in Fig. 3d. In a perfect trial $MDC = 0$.

An **Orthogonal Direction Change** (***ODC***) occurs when the tangent of the cursor path is perpendicular to the Task Axis; this happens four times in Fig. 3e. The algorithm to calculate *ODC* is similar to the one used for *MDC*, but we use x coordinates instead of y. In a perfect trial $ODC = 0$.

The five metrics above characterize the cursor path by logging discrete events, and they are scalars. We calculate them as the number of total incidents per session divided by the number of trials per session.

The following three metrics have pixels as a unit of measurement, and they complete the set of parameters proposed by McKenzie *et al.* [37]. Their calculation is again an average per session, accumulating resulting pixels from all trials and dividing the sum by the number of trials.

For **Movement Variability** (***MV***) we first calculate the average distance of the path followed from the Task Axis for all sampled points of the trial (Fig, 3f). If y_i is the current cursor distance, and $\bar{y}$ is the average distance, then *MV* is given by the formula:

$$MV = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n-1}} \tag{6}$$

where n is the number of trajectory samples taken for the current trial, and y_i is the distance of each cursor position sample point from the Task Axis, assuming that $y = 0$ on the Task Axis, positive above it, and negative below it. In a perfect trial $MV = 0$.

The **Movement Error** (***ME***) is the mean absolute value per trial of the cursor path distance from the Task Axis. This metric accumulates absolute distances, i.e., regardless of whether the cursor is above or below the Task Axis.

The formula calculates the *ME* value:

$$ME = \frac{\sum_{i=1}^{n}|y_i|}{n} \tag{7}$$

In a perfect trial $ME = 0$.

The **Movement Offset** (***MO***) parameter calculates for every move the total average distance of the cursor's track from the Task Axis. The formula gives the *MO* value:

$$MO = \bar{y}_i \tag{8}$$

where y_i is the distance of each cursor position sample point from the Task Axis. The difference of this metric from *ME* is that in *MO* negative distances (below the Task Axis) compensate for positive ones. In a perfect trial $MO = 0$.

C. NEW METRICS

We introduce the following three new quantitative parameters, which can describe the movement smoothness of a point-and-click task. For all of them, we calculate the velocity using the Pythagorean distance between two consecutive cursor positions sampled every 10ms (100Hz frequency) and is measured in pixels/ms (Fig. 4a).

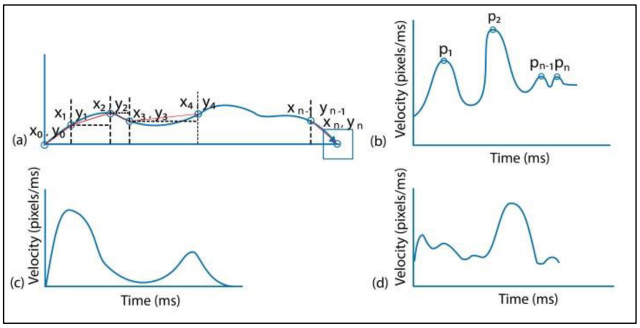

FIGURE 4. (a) Trajectory illustration example for the calculation of mean velocity (MVE) using the pythagorean distance, (b) velocity/time graph with velocity peaks (VP), (c) velocity/time graph with two peaks and deep valleys resulting in a lower maximum/mean velocity ratio (VR) value, and (d) velocity/time graph with a series of submovements with shallower valleys between velocity peaks resulting in lower VR value.

Mean Velocity (***MVE***) represents the average cursor speed during each trial. The mean value of velocity for a trial can be calculated by adding all instantaneous velocities (between 2 consecutive samples which represent the distance covered by the cursor in a 10ms time frame) and dividing by the number of samples that the trial comprises minus 1 (Fig. 4a). The Mean Velocity for each session is calculated in pixels/ms by the following formula:

$$MVE = \frac{v_0 + v_1 + \cdots + v_n}{(n-1)} \tag{9}$$

where v_i is the instantaneous velocity in pixels/ms:

$$v_i = \frac{\left(\sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2}\right)}{10\text{ms}} \qquad i = 0, 1, 2, \cdots, n \tag{10}$$

Velocity Peaks (***VP***) is a quality metric of the movement smoothness computed using the velocity profile in each trial (Fig. 4b). We define pi as the presence of a local maximum on the cursor velocity graph over time (Fig. 3b). $\mathrm{p_i}$ will take the value 1 if a local maximum is detected, or the value 0 in the case of a local maximum absence. *VP* represents movement changes from acceleration to deceleration. We calculate Velocity Peaks by counting the number of times the velocity of the cursor movement monotony changes from ascending to descending during each trial. These monotony changes are measured by partitioning the velocity data samples to groups of three (e.g., $[v_1, v_2, v_3]$ and $[v_2, v_3, v_4]$), then calculating the median value of each group (e.g., $\mathrm{m_1} = \text{median }[v_1, v_2, v_3]$, $\mathrm{m_2} = \text{median }[v_2, v_3, v_4]$) and finally comparing the median values. A local maximum value is present when $\mathrm{m_1} > \mathrm{m_2}$ and counts a descending monotony change ($\mathrm{p_i}$).

The following formula calculates *VP*:

$$\sum\nolimits_{i=1}^{n} p_i \tag{11}$$

Maximum/Mean Velocity Ratio (*VR*) is a metric that gives the ratio of the highest attained velocity value to the mean velocity value during each trial. In the presence of movement disorders, this metric can detect alterations of the movement pattern related to acceleration and deceleration periods as shown in Figures 4c and 4d. *VR* can showcase the impact of the highest attained velocity on the mean velocity.

The following formula calculates *VR*:

$$VR = \frac{MaxVelocity}{MeanVelocity} \tag{12}$$

In summary, the 13 performance and accuracy metrics used in IDEA are:

- Movement time (*MT*)
- Throughput (*TP*)
- Missed Click (*MCL*)
- Target Re-Entry (*TRE*)
- Task Axis Crossing (*TAC*)
- Movement Direction Change (*MDC*)
- Orthogonal Direction Change (*ODC*)
- Movement Variability (*MV*)
- Movement Error (*ME*)
- Movement Offset (*MO*)
- Mean Velocity (*MVE*)
- Velocity Peaks (*VP*)
- Maximum/Mean Velocity Ratio (*VR*)

The calculation of the above 13 metrics is an average per session, accumulating all values from all trials and dividing the sum by the number of trials.

III. EXPERIMENTAL SETTING

For the experiments, we used a desktop computer running Microsoft Windows 2000 with a 17-inch LCD monitor at a 1024 × 768 screen resolution, a wired keyboard, and a wired Microsoft Basic Optical Mouse. For the IDEA software development, we used Microsoft Visual Basic 6.0. The IDEA system collects the cursor movement samples with a rate of 100 samples per second as standard pixel coordinates of the mouse pointer position on the computer screen.

A. PROCEDURE

A familiarization phase of at least 15 minutes, precedes the experiment. During this phase, an instructor briefly describes the experiments and demonstrates how to complete each task with varying difficulty. For further assistance, the instructor orally directs the user to aim and click as close to the center of the targets as possible.

The experiments comprise three sessions, each with a different Index of Difficulty (*ID*), specified by three different target size and distance combinations. In the 1D experiment, targets are rectangular, and each session consists of 20 repetitions of moves (trials). The first trial starts from the center of the left target and requires the selection of the right target to complete. The second trial starts from the center of the right target and ends with the selection of the left one. Consequently, trials are back and forth moves, and we have 20 trials per session, giving us 60 trials per experiment. In the 2D experiment, we have 16 square targets in a circular layout, and each session consists of 17 repetitions of moves (trials). The first trial starts from the uppermost target and requires the selection of the opposite (bottom) target to complete successfully. The second trial starts from the bottom target and ends with the selection of the target next to the top one (on the right) and so-on clockwise until the top target is selected. Therefore, we have 17 trials per session, giving us 51 trials per experiment. For the three sessions, we used three different Indexes of Difficulty namely $ID_1 = 2.3$, $ID_2 = 3.2$, and $ID_3 = 4.1$. These *ID*s correspond to 3 different target widths, namely 76, 37, and 19 pixels for the 1D experiment, and 59, 28, and 14 pixels for the 2D experiment. The target height for the 1D experiment is fixed to 150 pixels, and their distance is fixed to 300 pixels, whereas in the 2D experiment the targets have equal width and height (they are squares), and their distance is fixed to 230 pixels.

B. PARTICIPANTS

Twenty-nine patients (age: 30.9 ± 1.7 years, males: 6, females: 23, education: 14, 1 ± 2.8 years) who had been hospitalized at the Demyelinating Diseases Section of the Neurological Clinic of Aeginition Hospital, National and Kapodistrian University of Athens, for the first episode of multiple sclerosis participated in the experiments. The results of the patients were compared with the results of 25 healthy volunteers (age: 30.2 ± 1.4, males: 5, females: 20, education: 16.3 ± 2.2 years). The participants' ages were between 18 and 55 years, and they were all right-handed.

C. MEDICAL PROTOCOL

All participants had a short mental status examination with an MMSE (Mini-Mental State Examination) score ≥ 24 [54]. They all confirmed that they fully understand the experimental process, and they signed their written consent for their participation. The research followed the tenets of the Declaration of Helsinki, and the ethical committee of the Aeginition Hospital approved the protocol.

Patient selection criteria:

- There should be a diagnosis of at least two focuses on brain MRI.
- No upper limbs locomotor deficit should be clinically apparent.
- Patient exclusion criteria included:
- Use of benzodiazepines, antidepressants, neuroleptics, alcohol for six months before the study.
- Presence of psychiatric, metabolic, endocrine or another organic disease.
- Presence of depression or anxiety.
- History of loss of consciousness, head injury or epilepsy.

- Taking corticosteroids on the previous month.
- Receipt of immunomodulatory or immunosuppressive treatment.
- MS relapse one month before the examination.
- Disturbance of visual acuity ($\leq$ 4/10), or color perception, or hearing.

The medical protocol includes four parts, all applied before the IDEA experiment. The first part consisted of a clinical assessment of the patient, based on EDSS (Expanded Disability Status Scale) score [5] and the 9 Hole Peg Test (assessment of the upper limbs' functionality) [8]–[12]. The clinical evaluation of patients with EDSS scale took place during the incident and at the stage of remission. Measurements were made at the stage of remission, at least one month after the complete discontinuation of treatment with corticosteroids. The second part consists of several tests including FSS (fatigue) [55], Zung (depressive symptoms) [56], CDS (derealization) [57], Eysenck (extraversion, neuroticism, psychoticism) [58]–[59], Sifneos (alexithymia) [60], LCB (control site scale) [61], and SCL-90 (scale of psychosomatic burden) [62]. The third part consists of several executive control and function tests: Stroop [63], Wisconsin test [64], Action Program Test, Key Search Test, Zoo Map Test, the executive control questionnaire (DEX) and CANDEX [65]. The fourth and last part was the IDEA system experiment.

None of the psychometric tests had a significant effect on any kinetic parameters of all four experiments, and consequently, there will be no further reference for the rest of this article.

D. DATA ANALYSIS AND STATISTICS

The IDEA system produces ASCII files containing the coordinates of the cursor's position on the screen, acquired every 10 ms. We used MATLAB version R2009b to calculate the 13 metrics described in the Methodology section.

We applied the following statistical analysis and tools to all the experiments' results (1D & 2D, Dominant & Non-Dominant Hand). Using the Kolmogorov-Smirnov test, we determined the normality of age distributions and experiment metrics. In the case of normality, we present all metrics using their mean values together with their standard errors and their corresponding 95% Confidence Intervals (CI). The matching of the control with the patient group regarding age and sex distribution was performed with the t-test and chi-square test (Fisher exact test) correspondingly. All thirteen IDEA metrics were subject to multivariate analysis of covariance (MANCOVA) with group and sex as the fixed factors and age as the covariate. Then, we applied univariate between-group comparisons with the necessary adjustments for multiple comparisons, and we extracted the effect of age on the metrics through the corresponding Pearson correlation coefficient (r). Finally, we input the test metrics as independent predictors in a hierarchical logistic regression model, with the group as the dependent variable, in order to assess the predictive value of the test concerning the two groups (patients & controls). The independence of the variables used in the regression model was verified using Pearson correlation, and additionally using the Rank-Score Characteristic (RSC) function that measures "cognitive diversity" as proposed in [66]. For the correlation method, we set the level of significance at 0.05. We performed all analyses using SPSS Statistics v23 [67].

IV. RESULTS

In all four experiments, the Kolmogorov-Smirnov test revealed that the distributions of age and all the metrics did not deviate from normality. Consequently, this justifies the use of parametric statistical procedures. The two groups were matched for age (controls: 30.2 ± 1.4, patients: 30.9 ± 1.7 years, t53= 0.29, p = 0.771) and sex (females/males 20/6 in controls and 21/8 in patients, χ21 = 0.15, p = 0.76).

TABLE 1. **Pearson correlation test for age, 1D experiment - dominant hand.**

Metric	r	p
MT	**0.237**	**0.002**
TP	**–0.259**	**0.001**
MCL	–0.009	0.905
TRE	0.082	0.293
TAC	0.057	0.464
MDC	0.022	0.778
ODC	0.093	0.487
MV	**0.180**	**0.021**
MO	0.152	0.051
ME	–0.055	0.481
MVE	–0.209	0.006
VP	**0.243**	**0.002**
VR	0.119	0.128

A. 1D EXPERIMENT – DOMINANT HAND

As Table 1 shows, in the 1D experiment for the dominant hand, the MANCOVA procedure revealed significant correlations ($p<0.01$) of age with Movement Time (r=0.237), Throughput (r=–0.259), Number of Velocity Peaks (r=0.243) and Movement Variability (r=0.18), $p<0.05$). The sex effect was focalized on differences in Movement Error ($p<0.05$), where women demonstrated a negative average of Movement Error (–2.5, 95% CI –3.9 to –1.1), while men had a positive average of Movement Offset (0.94, 95% CI –1.2 to 1.4).

The significant effect of the group spread to three metrics, namely Task Axis Crossing (p=0.012), Movement Variability (p=0.000), and Movement Offset (p=0.002). Patients had significantly higher mean values than controls in all three metrics. The mean Movement Variability in the patient group was almost 50% higher than the Controls group, and Movement Offset significantly differed.

The results of the hierarchical logistic regression model for the 1D experiment and the dominant hand, revealed that the inclusion of just two predictors, namely Movement Variability and Task Axis Crossing can correctly predict the group

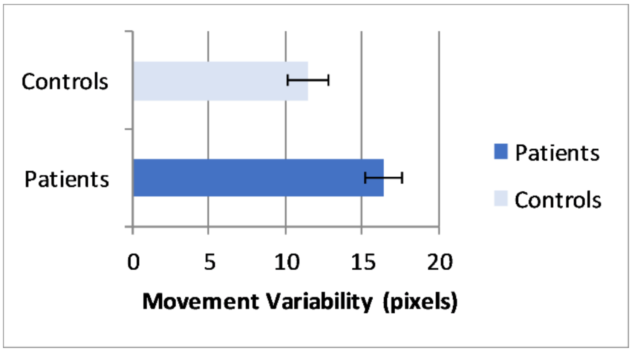

FIGURE 5. Movement variability (MV) comparison between patients and healthy participants.

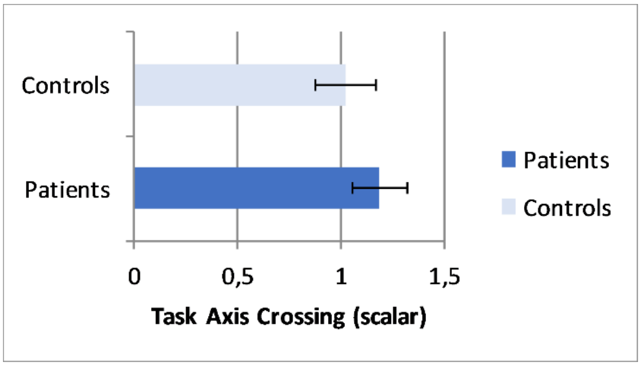

FIGURE 6. Task axis crossing (TAC) comparison between patients and healthy participants.

membership of 16/26 controls and 22/29 patients, giving a total of correct classifications 38/55 = 69.1%, which is significantly larger than the 50% that would be achieved by chance. As Fig. 5 illustrates, the mean value of Movement Variability for controls is lower than the value for patients.

In Fig. 6 we see that controls score a Task Axis Crossing value of 1.02 which is almost 15% lower than the patients' score. We note that before conducting the regression model calculations, we conducted a Pearson correlation analysis between all metric pairs. The analysis for the two predictor variables (*MV* and *TAC*) showed no significant correlation between them at the 0.05 level. Table 2 shows the mean values and standard deviations of all metrics for both groups.

B. 1D EXPERIMENT - NON DOMINANT HAND

As Table 3 shows, in the 1D experiment for the non-dominant hand, the MANCOVA procedure revealed significant correlations ($p < 0.01$) of age with Movement Offset ($r = -0.204$), Mean Velocity ($r = -0.240$), as well as with Movement Time ($r = 0.195$, $p < 0.05$), and Throughput ($r = -0.201$, $p < 0.05$). The sex effect was focalized on differences in Movement Direction Change ($p < 0.01$) and Movement Error ($p < 0.05$). In the former metric, women demonstrated an average of Movement Direction Change (6.5, 95% CI –8.97 to –0.76), while men had an average of Movement Offset (11.42, 95% CI –10.01 to 0.27). In the latter metric, women demonstrated a negative average of Movement Error (–1.7, 95% CI –6.27 to –1.1), while men had an average of Movement Offset (3.5, 95% CI –5.7 to –1.69).

TABLE 2. Mean metrics and standard deviations, 1D experiment - dominant hand.

1D Experiment Dominant Hand	Patients		Controls	
Metric	Mean	SD	Mean	SD
MT (msec)	980.50	296.50	963.10	340.50
TP (bits/sec)	4.14	1.02	4.49	1.29
MCL (scalar)	1.73	1.82	1.38	2.03
TRE (scalar)	0.85	0.55	0.86	0.63
***TAC* (scalar)**	**1.18**	**0.40**	**1.02**	**0.42**
MDC (scalar)	9.60	19.01	13.20	22.97
ODC (scalar)	7.40	3.70	8.90	3.41
***MV* (pixels)**	**16.40**	**5.60**	**11.40**	**2.30**
ME (pixels)	21.80	7.10	17.20	7.84
***MO* (pixels)**	**–2.53**	**7.96**	**0.90**	**4.30**
MVE (pixels/ms)	0.44	0.10	0.45	0.08
VP (scalar)	60.00	19.03	58.00	18.02
VR (scalar)	19.41	6.10	21.27	8.60

TABLE 3. Pearson correlation test for age, 1D experiment - non dominant hand.

Metric	r	p
MT	**0.195**	**0.012**
TP	**–0.201**	**0.010**
MC	0.075	0.338
TRE	–0.018	0.818
TAC	0.046	0.559
MDC	–0.065	0.410
ODC	0.250	0.578
MV	–0.039	0.616
ME	0.051	0.516
MO	**–0.204**	**0.008**
MVE	**–0.240**	**0.002**
VP	0.116	0.137
VR	0.091	0.244

The hierarchical logistic regression model's results for the 1D experiment and the non-dominant hand, revealed that the inclusion of three predictors, namely Movement Time, Movement Error and Mean Velocity could correctly predict the group membership of 17/26 controls and 20/29 patients, giving a total of correct classifications 37/55 = 67.3%, which is significantly larger than the 50% that would be achieved by chance. Fig. 7 illustrates that patients scored a negative Movement Error (*ME*) value in comparison to the matched controls who scored a positive one. Moreover, Fig.8 shows that patients scored a lower Mean Velocity value than the matched controls. Finally, in Fig.9, we can see that the difference in Movement Time values between the two groups does not seem so great, but it is still significantly different statistically. Just like in the 1D experiment for the dominant hand, we run a Pearson correlation analysis between all metric pairs before conducting the regression model calculations. The analysis

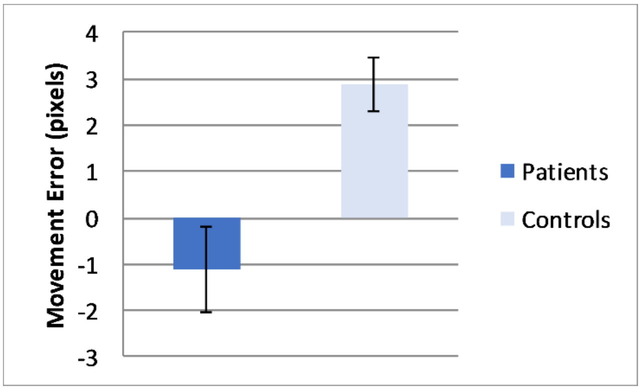

FIGURE 7. Movement error (ME) comparison between patients and healthy participants.

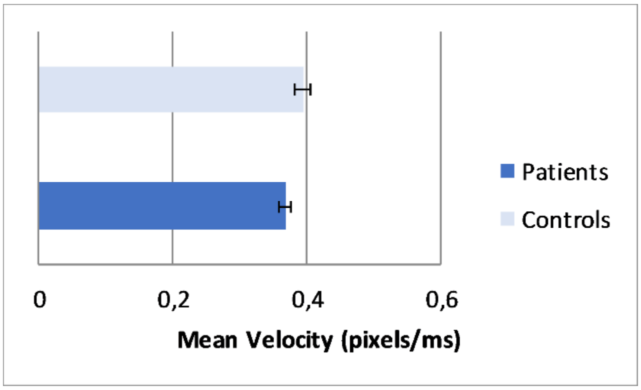

FIGURE 8. Mean velocity (MVE) comparison between patients and healthy participants.

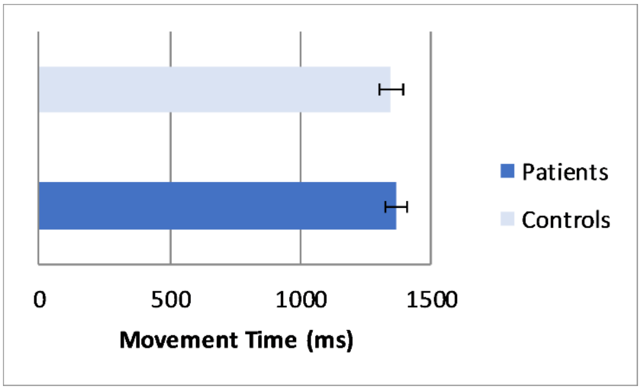

FIGURE 9. Movement time (MT) comparison between patients and healthy participants.

for the three predictor variables (*ME*, *MVE* and *MT*) showed no significant correlation between them at the 0.05 level. Table 4 presents the mean values and standard deviations of all metrics for both groups.

TABLE 4. Mean metrics and standard deviations, 1D experiment - non dominant hand.

1D Experiment Non-Dominant Hand	Patients		Controls	
Metric	Mean	SD	Mean	SD
***MT* (msec)**	**1364.87**	**377.16**	**1346.03**	**388.14**
TP (bits/sec)	2.86	0.72	2.78	0.88
MCL (scalar)	1.48	1.66	1.24	1.21
TRE (scalar)	1.07	0.65	1.29	0.76
TAC (scalar)	1.07	0.30	1.00	0.34
MDC (scalar)	7.07	11.07	8.60	12.57
ODC (scalar)	5.44	9.07	7.63	10.54
MV (pixels)	26.10	17.07	22.05	16.91
***ME* (pixels)**	**–1.12**	**8.63**	**2.88**	**5.18**
MO (pixels)	27.13	13.43	23.04	13.92
***MVE* (pixels/ms)**	**0.36**	**0.09**	**0.39**	**0.11**
VP (scalar)	88.54	26.13	85.00	26.03
VR (scalar)	27.69	23.13	25.38	10.67

TABLE 5. Pearson correlation test for age, 2D experiment - dominant hand.

Metric	r	p
MT	**0.26**	**0.00**
TP	**–0.29**	**0.00**
MCL	–0.01	0.89
TRE	0.04	0.62
TAC	0.12	0.12
MDC	0.07	0.39
ODC	0.07	0.14
MV	**0.25**	**0.00**
ME	**0.28**	**0.00**
MO	**0.25**	**0.00**
MVE	–0.01	0.88
VP	**0.31**	**0.00**
VR	**0.27**	**0.00**

C. 2D EXPERIMENT - DOMINANT HAND

As Table 5 shows, in the 2D experiment for the dominant hand, the MANCOVA procedure revealed significant correlations ($p < 0.01$) of age with Throughput ($r = –0.294$), Movement Error ($r = 0.278$), Number of Velocity Peaks ($r = 0.492$), Velocity Ratio ($r = 0.268$), as well as with Movement Time ($r = 0.258$, $p < 0.05$), Movement Variability ($r = 0.252$, $p < 0.05$), and Movement Offset ($r = 0.253$, $p < 0.05$). The sex effect did not show any significant correlations among the thirteen parameters. Finally, one sample t-tests revealed no significant difference among the 13 parameters' mean values showing that the group effect had no significant impact.

For the dominant hand in the 2D experiment, the results of the hierarchical logistic regression model revealed that the inclusion of just three predictors, namely Missed Clicks, Movement Variability, and Mean Velocity can correctly predict the group membership of 17/26 controls and 22/29 patients, giving a total of correct classifications 39/55 = 70.9%, which is significantly larger than the 50% that would be achieved by chance. Fig. 10 shows that patients scored a higher Missed Clicks (*MCL*) value by almost 30% in comparison to the matched controls. Additionally, in Fig.11,

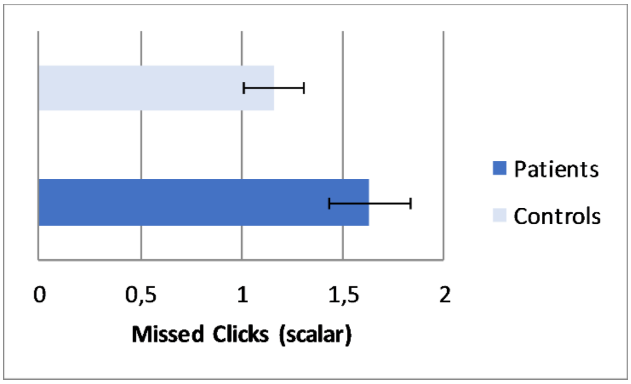

FIGURE 10. Missed clicks (MCL) comparison between patients and healthy participants.

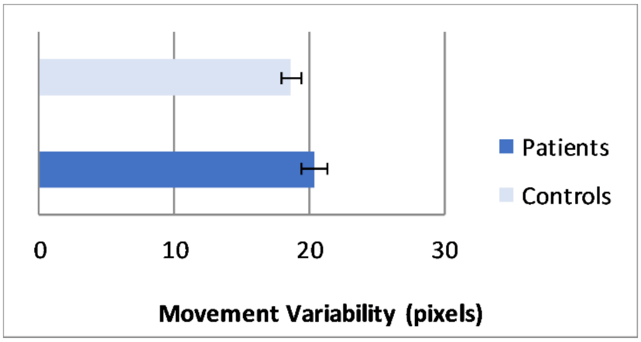

FIGURE 11. Movement variability (MV) comparison between patients and healthy participants.

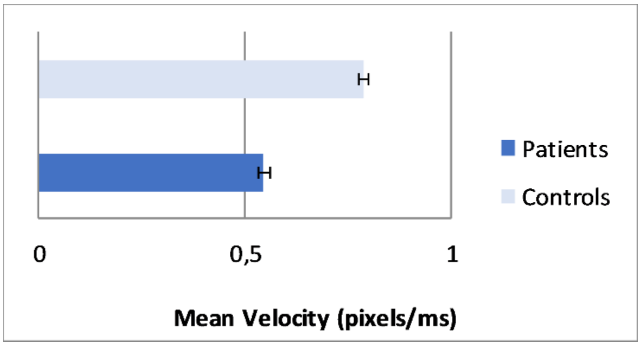

FIGURE 12. Mean velocity (MVE) comparison between patients and healthy participants.

we can see that the difference in Movement Variability values between the two groups is quite close but still significantly different statistically. Furthermore, in Fig.12 it is evident that controls scored a much higher Mean Velocity value compared to the patients. Just like in the other experiments, we run a Pearson correlation analysis between all metric pairs before conducting the regression model calculations. The analysis for the three predictor variables (*MCL*, *MV*, and *MVE*) showed no significant correlation between them at the 0.05 level. Table 6 presents the mean values and standard deviations of all metrics for both groups.

TABLE 6. Mean metrics and standard deviations, 2D experiment dominant hand.

2D Experiment Dominant Hand	Patients		Controls	
Metric	Mean	SD	Mean	SD
MT (msec)	1298.05	508.47	1194.98	376.40
TP (bits/sec)	4.34	1.20	4.44	1.05
***MCL* (scalar)**	**1.63**	**1.90**	**1.16**	**1.33**
TRE (scalar)	0.70	0.46	0.69	0.45
TAC (scalar)	0.29	0.14	0.26	0.13
MDC (scalar)	22.15	14.50	19.76	10.45
ODC (scalar)	24.40	9.50	21.86	7.98
***MV* (pixels)**	**20.41**	**8.58**	**18.65**	**6.53**
ME (pixels)	17.60	6.35	15.87	4.52
MO (pixels)	19.41	6.72	18.29	5.58
***MVE* (pixels/ms)**	**0.54**	**0.13**	**0.78**	**0.10**
VP (scalar)	80.90	24.57	77.52	23.38
VR (scalar)	20.24	7.16	19.43	6.92

TABLE 7. Pearson correlation test for age, 2D experiment - non dominant hand.

Metric	r	p
MT	0.144	0.065
TP	–0.152	0.051
MCL	0.126	0.106
TRE	–0.051	0.514
TAC	0.137	0.080
MDC	0.069	0.382
ODC	0.256	0.225
MV	0.077	0.327
MO	0.040	0.614
ME	0.049	0.532
MVE	–0.143	0.066
VP	0.099	0.206
VR	0.042	0.593

D. 2D EXPERIMENT - NON DOMINANT HAND

Table 7 shows that in the 2D experiment the MANCOVA procedure revealed no significant correlations ($p < 0.05$) of age among the thirteen parameters. On the other hand, the sex effect showed a significant correlation with Task Axis Crossing ($r = 0.189$, $p < 0.05$). Finally, one sample t-tests revealed no significant difference among the 13 parameters' mean values showing that the group effect had no significant impact.

For the non-dominant hand in the 2D experiment, the results of the hierarchical logistic regression model revealed that the inclusion of three predictors, namely Target Re-Entry, Throughput, and Mean Velocity could correctly predict the group membership of 14/26 controls and 20/29 patients, giving a total of correct classifications $34/55 = 61.8\%$, which is significantly larger than the 50% that would be achieved by chance. Fig. 13 shows that patients scored a higher Target Re-Entry (*TRE*) value by almost 6% in comparison to the matched controls. Besides, in Fig.14, we can see that controls scored a slightly higher Throughput

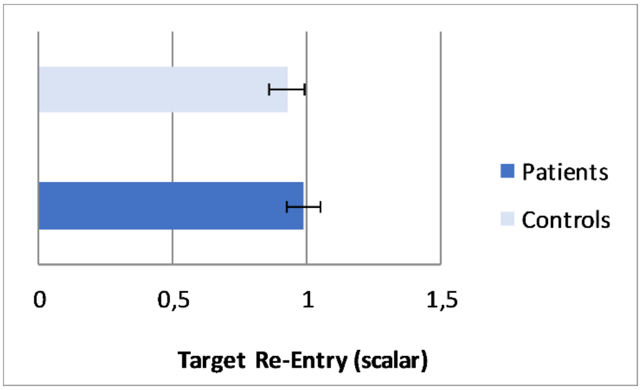

FIGURE 13. Target re-entry (TRE) comparison between patients and healthy participants.

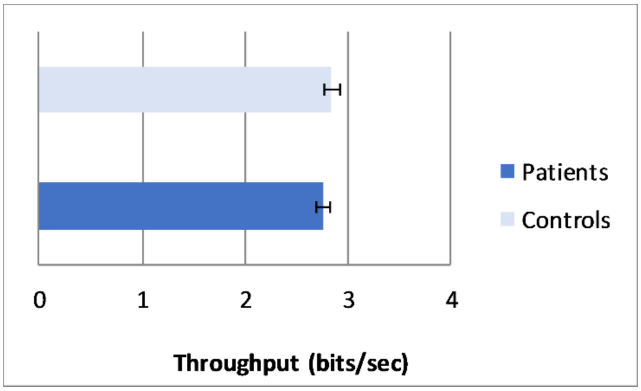

FIGURE 14. Throughput (TP) comparison between patients and healthy participants.

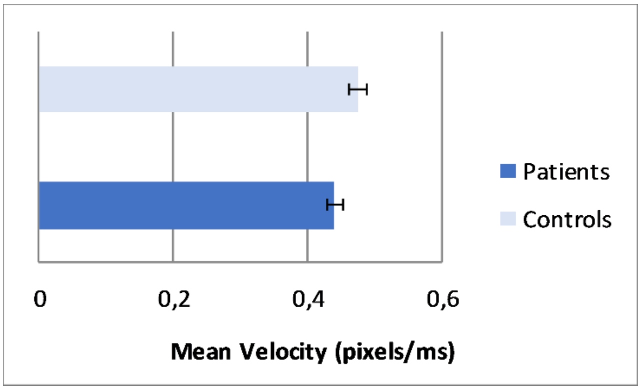

FIGURE 15. Mean velocity (MVE) comparison between patients and healthy participants.

value in comparison to the patients' group value. Finally, in Fig. 15 the controls' Mean Velocity value is a little higher than the patients' value. As in the previous experiments, we run a Pearson correlation analysis between all metric pairs before conducting the regression model calculations. The analysis for the three predictor variables (*TRE*, *TP*, and *MVE*) showed no significant correlation between them at the 0.05 level. Table 8 shows mean values and standard deviations of all metrics for both groups.

TABLE 8. Mean metrics and standard deviations, 2D experiment - non dominant hand.

2D Experiment Non-Dominant Hand	Patients		Controls	
Metric	Mean	SD	Mean	SD
MT (msec)	1878.24	576.46	1770.16	464.12
***TP* (bits/sec)**	**2.75**	**0.69**	**2.84**	**0.68**
MCL (scalar)	2.25	2.52	1.85	2.09
***TRE* (scalar)**	**0.98**	**0.58**	**0.92**	**0.57**
TAC (scalar)	0.37	0.16	0.36	0.16
MDC (scalar)	28.11	16.20	27.80	13.37
ODC (scalar)	24.44	108.80	22.04	7.99
MV (pixels)	31.04	12.44	27.83	10.41
ME (pixels)	23.47	7.89	22.38	8.13
MO (pixels)	27.77	9.60	25.98	9.35
***MVE* (pixels/ms)**	**0.43**	**0.11**	**0.47**	**0.12**
VP (scalar)	127.30	41.20	119.28	34.40
VR (scalar)	25.08	9.19	25.20	16.19

V. DISCUSSION

A careful observation of the results indicates that there were significant correlations between the variables of interest and the kinematic parameters in all four experiments. Specifically, in the majority of the experiments, the correlation of age with Movement Time and Throughput signifies that, as people get older, they require more time to perform each move and they score a reduced Throughput. Moreover, in the 1D experiment for the non-dominant hand, and the 2D experiment for the dominant hand, the age correlation with Movement Error and Movement Offset shows a decline in movement accuracy as people grow older. The correlation of age with the Ratio between Max and Mean Velocity, in the 2D experiment for the dominant hand, reveals that older people have a slower and more uneven movement between targets, whereas the Number of Velocity Peaks in the same experiment shows a decline in their movement smoothness. We note that the RSC analysis [66] of the metrics did not conclude to be more precise than the score analysis, so it did not affect the Pearson correlation results.

In comparison with relevant results [68] previously reported that are based on the ISO 9241 standard and mouse devices, the 1D experiment of MacKenzie and Jusohin [69] reveals a Throughput score of 3.7 bits/sec for an *ID* range 1.0 - 4.1 bits. This is lower than our Throughput mean value of 4.49 bits/sec (1D experiment, Dominant Hand, *ID*s range 2.3 - 4.1 bits) but inside its SD variation (±1.29 bits/sec). For the 2D experiment, the study of Oh and Sturzlingerthe [70] showcases a Throughput of 4.09 bits/sec (*ID*s between 2.58 and 3.75 bits), whereas MacKenzie *et al.* [37] report 4.9 bits/sec for an *ID* of 3.8 bits, values that are in the range of our results (4.44±1.05 bits/sec, Dominant Hand). Other studies on 2D mouse-based pointing tasks report Throughput values of 4.9 bits/sec [71] and 3.99 ± 0.32 bits/sec [72] respectively. Differences in Throughput values between the above studies are quite expected due to the variety of mouse types, dpi settings, monitor sizes, and user familiarization.

A significant difference of mean values between controls and patients in Task Axis Crossing, and Movement Variability in the 1D Experiment – Dominant Hand is apparent. This result reveals that patients make greater effort to move the cursor from the start point to finish point in a straight line compared to healthy participants. The difference between the two groups is also apparent in Mean Velocity and Target Re-Entry metrics, which brings to the surface the tendency of patients to make more jerky movements than the controls.

In all four experiments it is clear that patients score a higher Movement Time value (1D Experiment - Dominant Hand: MT = 980.45 msec, SD = 217.32, 1D Experiment - Non Dominant Hand: MT = 1364.87, SD = 377.16, 2D Experiment - Dominant Hand: MT = 1298.05 msec, SD = 508.47, 2D Experiment - Non Dominant Hand: MT = 1878.24, SD = 576.46) in comparison to the matched controls (1D Experiment - Dominant Hand: MT = 963.06 msec, SD = 340.52, 1D Experiment - Non Dominant Hand: MT = 1346.03, SD = 388.14, 2D Experiment - Dominant Hand MT = 1194.98, SD = 376.4, 2D Experiment - Non Dominant Hand: MT = 1770.16 msec, SD = 464.12). This is also mentioned in the relative study that we referred to in the introduction [25], according to which patients spend a significantly longer time in completing movement tasks, as well as more effort for making corrections while approaching a target (MT = 684 msec, SD = 240.35) than controls (MT = 495 msec, SD = 183.53). This result enforces the suggestion that computerized pointing tasks can evaluate motor deficits of upper limbs and that accuracy-related kinematic parameters could enhance the overall upper limbs motor assessment.

Another interesting aspect of our experiments is the effect of the dominant and non-dominant hand across the kinematic parameters. Notably, in both dimensions, the values of Throughput, Mean Velocity and Number of Velocity Peaks for the dominant hand are quite higher compared to the non-dominant ones. Furthermore, for the non-dominant hand, we can see a significant increase of Movement Time and Orthogonal Direction Change in comparison to the dominant hand experiments. All the above, conclude that the Dominant Hand is overall more accurate and easy to control than the Non-Dominant Hand, making it more suitable performance-wise in dexterity tasks.

Taking into consideration that the logistic regression equation predicted correctly: 1) the 69.1% of the classifications in the 1D experiment for the Dominant Hand, 2) the 67.3% of the classifications in the 1D experiment for the Non-Dominant hand, 3) the 70.9% of the classifications in the 2D experiment for the Dominant Hand, 4) the 61.8% of the classifications in the 2D experiment for the Non-Dominant Hand, and the fact that the examined patient sample has no apparent clinical motor deficits, we can claim that the IDEA system can be potentially useful as a reliable prediction tool with notable sensitivity for the early detection of MS.

Concerning the three newly introduced metrics in the IDEA system and their impact on the evaluation of motor deficits, some authors also refer to Velocity Peaks (VP) as ''movement units'' [73], [74]. With the presence of movement disorders, the VP number increases resulting in a less smooth movement. As Rohrer *et al.* [74] found during the recovery of stroke patients, when their movement skills ameliorate, the velocity profile of the hand movement presents fewer peaks resulting in a smoother movement. VP as a commonly used smoothness metric counts the number of local maxima in the speed profile to quantify smoothness. It appears that this simple method performs reasonably well on the movements made by stroke patients [31].

We also note that the reciprocal of metric Velocity Ratio ($1/VR$) has been used by other studies as a measure for reaching movements and path drawing [14], [75], [76], according to which, in early recovery from stroke, the movements of patients with upper limb deficits appear to be composed of a series of short, episodic sub-movements.

Taking into consideration the possibility of using several other devices like Microsoft Kinect [42] and Wiimote [41] with IDEA, there is further certainty that more advanced and complicated devices could take advantage of its capabilities in future studies. More specifically, robotic therapy research has shifted towards exoskeleton robots with some commercially available rehabilitation devices for the upper limb, such as the Armeo products [75]–[77]. Moreover, some early studies show that Virtual Reality technology is starting to make some initial steps towards upper limb rehabilitation for patients with stroke [78]. In accordance with several other relative studies on rehabilitation robotics for upper limbs [16]–[19] specific muscles of the upper limbs could be tested and trained by implementing certain repetitive visual tasks on the screen beside the 1D and 2D trials discussed above, (e.g., 3D, labyrinths, paths) and additionally provide haptic feedback information, depending on a programmable input device [43]. Finally, the IDEA system's assessment procedure makes it possible to measure and evaluate upper limb motor behavior in an objective fashion. This type of assessment can prove to be a good supplement to standard clinical assessments as it provides objective, sensitive, and detailed information about a subject's motor ability. The semi-automated nature and ease of administration have allowed for the possibility of assessing motor performance at more frequent intervals than possible with standard assessment techniques, and as a result, it may help drive the development of sensory retraining techniques [79].

VI. CONCLUSION

We have presented an enhanced version of the IDEA system as an objective, highly sensitive and reliable method for evaluating the upper limb motor skills performance. By introducing three new metrics for the point-and-click cursor trajectory analysis, along with the application of the two-dimensional experiment in the case of MS, we have found that the reliability and validity of the previous prediction model (1D experiment) [32] has been improved. Particularly, comparing this result with the one in our previous work, we see that the parameters representing movement smoothness have an essential impact on motor skill evaluation. Also, the comparison results between the dominant and the non-dominant hand indicate that there is room for further studies regarding the relation of both hands motor skills wise. The results lead to conclusions that can allow for a better understanding of the early-stage multiple sclerosis' effect on the upper limbs of the human body. We can claim that the IDEA system can be potentially used as a reliable prediction tool with notable sensitivity and reliability that could apply to other diseases that affect the kinematics of the upper limbs.

Based on the additional capabilities of the IDEA system (e.g., various 2D and 3D input devices, multidimensional tests, and flexible user interface) we expect that further future studies could adequately review the newly introduced kinematic parameters that give evidence of the derived motor impairment. Ongoing studies include investigation of the IDEA based detection capabilities in Learning Difficulties, including the cases of minimal brain dysfunction, dyslexia, and dysphasia [80].

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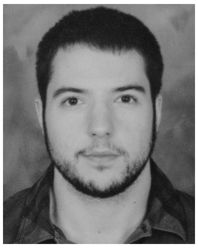

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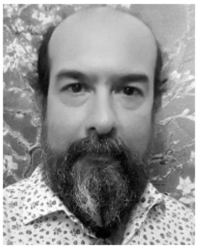

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