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Research Paper

Clinical application and new visualization techniques of 3D-quantitative motion analysis in epileptic seizures characterized by ictal automatic movements

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ABSTRACT

Purpose: Our aim was to test the capability of the NeuroKinect 3D-method, as a movement visualization technique and quantitative analysis to differentiate ictal movements such as hyperkinetic and focal seizures with manual automatisms. The dataset is extracted from the NeuroKinect dataset, which is a RGB-D-IR dataset of epileptic seizures. The dataset is recorded with Kinect v2 and consists of RGB, Infrared (IR) and depth streams. Quantitative 3D-movement analysis of 20 motor seizures was performed. Velocity, acceleration, jerk, covered distance, displacement and movement extent of Regions of Interests (= ROI: head, right hand, left hand and trunk) were captured.

Results: Among the analyzed seizures were 10 hyperkinetic (n = 7: 4 male, 3 female; mean age 39.6 years (SD ± 9.7)) and 10 focal seizures with manual automatisms (n = 10: 2 male, 8 female; mean age 39.2 years (SD ± 17.6)). Hyperkinetic seizures exhibited higher mean velocity in all ROIs (e.g. head = 0.62 ± 0.28 (m/s) vs. 0.12 ± 0.07 (m/s)) as well as higher mean acceleration and mean jerk in most ROIs; these differences were statistically significant. Mean movement extent, covered distance, and displacement for all ROIs were larger for hyperkinetic seizures, however not significantly. The duration of ictal movements (80 s ± 38 s versus 26 s ± 14 s; p = 0.001) was significantly longer in focal seizures with manual automatisms.

Conclusions: This new visualization technique allows to reconstruct tracked movement via 3D viewer and supports a 3D movement quantification which is capable to differentiate seizures characterized by movements, which may help to localize the epileptogenic zone.

1. Introduction

The analysis of epileptic seizure semiology is an important tool to identify the localization of the epileptogenic zone in patients considered for epilepsy surgery [1–3]. Some seizure types characterized by movements have a high localizing value. For instance, focal onset seizures with impaired awareness and automatisms [4] (automotor seizures [5]) which are preceded by abdominal auras are highly associated with temporal lobe epilepsy [6]. On the other hand, hyperkinetic seizures were frequently observed in patients with frontal lobe epilepsy [7]. Seizures originating in the cingulate cortex present complex behaviours, often with emotional components [8]. Specific ictal manifestations such as body pronation, tonic/dystonic posturing, and vocalizations varied along the rostro-caudal axis of the cingulate cortex. A quantitative analysis of hyperkinetic seizures identified three clusters that correlated with different patterns of anatomic localization of the seizure onset zone: Cluster 1 was characterized clinically by asymmetric hyperkinetic movements with dystonia and vocalization (mainly parietal seizures), Cluster 2 had bilateral and symmetrical stereotyped hyperkinetic movements without dystonia (temporal seizures and prefrontal dorsolateral seizures), Cluster 3 was characterized by seizures with emotions and vocalizations, bilateral and symmetrical hyperkinetic movements

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and integrated behaviour (temporal seizures and a majority of prefrontal (ventromesial) seizures) [9]. The study emphasized that specific ictal signs are typical for frontal lobe epilepsy but there can be overlapping semiologies in different locations. Thus, they advocated a multimodal approach, combining semiology with other diagnostic tools, to enhance localization accuracy. Another approach to categorize frontal seizures in terms of semiology was made by Bonini et al [10]: four main groups of patients were identified according to semiologic features, and correlated with specific patterns of anatomic seizure localization. The more anterior the seizure organization, the more likely was the occurrence of integrated behaviour during seizures. Distal stereotypies were associated with anterior prefrontal regions and proximal stereotypies with posterior prefrontal areas. Analysis of seizure semiology is currently based on the visual interpretation of 2D video-EEG data in epilepsy monitoring units (EMUs) by highly specialized clinicians [2,3], but limited by a high interrater variability [11].

2. Related work

Deep learning (DL) methods have revolutionized many areas of medical diagnostics, including video and signal analysis [12]. However, while DL systems are increasingly applied in clinical contexts, they typically focus on classification or detection and do not provide detailed quantification or visualization of movement patterns.

Computer vision systems have been developed to analyse patient movement using video data [13,14]. In a comprehensive review, Karácsony et al and Ahmedt-Aristizabal et al both discussed those advancements [15,16]. The integration of computer vision and deep learning techniques has proven valuable for motion detection and action recognition, with several studies demonstrating high sensitivity in video-based seizure detection [17–19]. Additionally, an automated seizure detection system using computer vision and independent component analysis has been proposed [20].

The use of computer vision and machine learning to automatically analyse and categorize seizures from video recordings has been an emerging field. An overview of the latest works can be found in Table 2 of Karácsony et al [15]. We proposed a 2-stage deep learning framework for in-bed movement action recognition using a single camera, demonstrating the growing interest in clinical movement analysis through vision-based systems [15]. A recent study also demonstrated that deep learning models utilizing facial appearance features and skeletal keypoints can accurately detect emotional expressions and dsytonic movements, respectively, in hyperkinetic seizures [21]. An automated classification of movement features could differentiate between TLE and FLE [22]. Recently, we published the feasibility of a 24/7 novel object and action recognition based deep learning (DL) monitoring system to differentiate between seizures in frontal lobe epilepsy (FLE), temporal lobe epilepsy (TLE) and functional, non-epileptic events [23].

Most of the previous quantitative approaches rely on 2D pose estimation to quantify motor behaviour. For instance, 2D skeletal tracking systems such as OpenPose have been widely used to quantify human movement, including in clinical and behavioural settings [24].

Our previous work also focused on objective, movement quantification methods to differentiate the movement patterns of seizure types [25–27]. Specifically, 2D-quantitative analysis allowed a differentiation of head version in frontal (FLE) and temporal lobe epilepsy (TLE) [28,29], and another study distinguished upper limb movements of FLE from TLE [27]. However, due to the limitations of two-dimensional analysis and limited video quality important components of the movements were often lost (e.g. movements perpendicular to the two-dimensional camera plane).

Building on this work, a novel 3D approach of our group reduced these limitations and provided a simpler, faster and lower-cost procedure than previous approaches to quantitatively analyse MOI patterns of epileptic seizures [30]. The tracking was carried out in cooperation between clinical and technological partners based on the DeepEpil concept [31].

As a next step, our aim was to clinically apply the NeuroKinect 3D-method to quantitatively differentiate more detailed seizures characterized by automatisms in different focal motor seizures such as hyperkinetic seizures and seizures with manual automatisms. To our knowledge, this is the first semi-automatic method to quantify in 3D these seizure types.

3. Methods

The utilized dataset is extracted from the NeuroKinect dataset, which is a unique RGB-D-IR dataset of epileptic seizures acquired in a collaboration by INESC TEC and the EMU of the University of Munich Epilepsy Centre. The main obstacle in building this patient collective was the video recording quality of seizures, to include seizures with minimal occlusions such as caretakers/nurses obstructing the camera, as it is an optical tracking method. Consequently, seizures with visible motor manifestations were chosen. The dataset is recorded with Kinect v2 and consists of RGB, Infrared (IR) and depth streams. It is recorded and stored in 512x424 resolution for IR and Depth, and 640x480 for RGB data with a full size of 2.7 TB and labelled with epileptic seizure types and semiology annotations.

From the above-described dataset, IR-D videos of 10 focal seizures with manual automatisms and 10 hyperkinetic seizures were extracted. In all seizures, the patients were tested by technicians and therefore can be labelled as focal seizures with impaired awareness according to the ILAE seizure classification [4]. Seizures were labelled as focal seizures with manual automatisms or hyperkinetic: the gold-standard to classify a seizure was, like in clinical routine, the evaluation of an expert clinical team via video-EEG, with a clinical consensus of at least 2 observers. The decision was based on what kind of complex movements were predominantly present in the seizure (focal seizures with manual automatisms: automatisms of the hands/fumbling, involvement of more distal body parts versus hyperkinetic where the main manifestations consist of complex movements involving the proximal segments of the limbs and trunk).

3.1. 3D movement tracking of seizures

The 3D movement tracking of the patients was carried out with the KiSA system [30]. It is a user-interactive algorithm, which utilizes optical flow and depth criteria to semi automatically track the Region Of Interest (ROI), in this case the head, the left or right hand, and the trunk. As we wanted to compare hyperkinetic movements to manual automatisms we had to find regions of interest that involve movement in both groups. Therefore, we chose the head, trunk and both hands, as most focal seizures with manual automatisms are characterized by distal automatisms (fumbling or picking at clothes) and hyperkinetic seizures involve the whole body mostly proximal. If we had chosen more proximal regions as shoulders/arms as ROI, which would have been more accurate to analyze hyperkinetic seizures, most of the movement of focal seizures with manual automatisms would have been missed. In earlier studies we established that extensive proximal shoulder movements during hyperkinetic seizures also resulted in larger movement extent of the wrist. The algorithm tracks the initially selected ROI, if the depth criteria is not satisfied an auto-correction process is initiated. In case it does not resolve the tracking with the depth criteria, the user is requested to interactively re-identify the tracking target. The tracked 3D positions for each ROI are defined in Eq. (1), where x, y, z are the relative 3D positions from the camera.

$$r_i = [\mathrm{x_i}, \mathrm{y_i}, \mathrm{z_i}] \tag{1}$$

As it is an IR + Depth method both daytime and nighttime epileptic seizures could be recorded. The tracking performance was qualitatively reviewed, if the performance was not satisfactory the tracking was

repeated until the performance was deemed acceptable in terms of the limitations of the approach.

3.2. Quantitative analysis

3.2.1. Metrics calculated and their definitions

From the tracked 3D coordinates the distance (Δs_I) between two consecutive tracked point ($r_{i,i+1}$) is defined by Eq. (2), where x, y, z are the 3D coordinates (Eq. (1)).

$$\Delta s_i = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2} \tag{2}$$

As potential quantitative biomarkers to discriminate between hyperkinetic seizures and focal seizures with manual automatisms the following six metrics were considered to describe each seizure.

Seizure mean velocity ($\bar{v}$) is defined by Eq. (3), seizure mean acceleration ($\bar{a}$) by Eq. (4) and seizure mean jerk ($\bar{j}$) by Eq. (5), where n is the number of frames, Δs_I is defined by Eq. (2), and $\Delta t_i = t_{i+1} - t_i$.

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n}\frac{\Delta s_i}{\Delta t_i} \tag{3}$$

$$\bar{a} = \frac{1}{n}\sum_{i=1}^{n}\frac{\Delta s_i}{\Delta t_i^2} \tag{4}$$

$$\bar{j} = \frac{1}{n}\sum_{i=1}^{n}\frac{\Delta s_i}{\Delta t_i^3} \tag{5}$$

The total covered distance (s_{tot}) during the seizure is the sum of all distances between consecutive tracked points (Eq. (6)).

$$s_{tot} = \sum_{i=1}^{n}\Delta s_i \tag{6}$$

The displacement (s_{disp}) during the seizure is defined by the distance between starting (r_1) and final (r_{end}) positions (Eq. (7)).

$$s_{disp} = \sqrt{(x_1 - x_{end})^2 + (y_1 - y_{end})^2 + (z_1 - z_{end})^2} \tag{7}$$

Movement Extent (V) is the volume defined by the endpoints of the movements on the axes (Eq. (8)).

$$V = (x_{max} - x_{min})^*(y_{max} - y_{min})^*(z_{max} - z_{min}) \tag{8}$$

3.2.2. Statistical considerations

The above-described metrics as quantitative biomarkers for each seizure were calculated. To aggregate the results of each class the mean of these quantitative movement parameters ($\overline{val_{sz}}$) was calculated.

$$\overline{val_{sz}} = \frac{1}{n}\sum_{i=1}^{n} val_n \tag{9}$$

In case of mean velocity, acceleration and jerk the mean of these parameters were calculated, and the standard deviation of the means, excluding the standard deviation of these parameters through individual seizures. This defines the inter-seizure average and standard deviation and separates the intra-seizure dynamics. To clarify, in the following the reported mean parameters are these class-wise mean parameters, not the seizure-wise mean parameters. To compare the two classes of hyperkinetic and focal seizures with manual automatisms Mann-Whitney U test was utilized, statistical significance was considered when $p < 0.05$. To counteract the problem of multiple comparisons the Holm–Bonferroni method [32] was used. It is intended to control the family-wise error rate (FWER).

4. Results

4.1. Quantitative movement analysis

4.1.1. Patient collective and demographic data

10 focal seizures with manual automatisms and 10 hyperkinetic seizures were analyzed, originating from 10 (eight female and two male) and seven (three female and four male) patients respectively. One patient was in both semiological groups as she had one focal seizure with manual automatisms and one hyperkinetic seizure. Nine patients were recorded with invasive electrodes (four with focal seizures with manual automatisms, five patients with hyperkinetic seizures). The mean age of the patients with focal seizures with manual automatisms was 39.2 years (SD ± 17.6 years) of those with hyperkinetic seizures 39.6 years (SD ± 9.7 years). All focal seizures with manual automatisms had a temporal seizure pattern, in all hyperkinetic seizures the seizure pattern started frontal. Regarding the overall syndrome and epileptogenic zone, the patients in whom we recorded seizures with manual automatisms had mainly temporal lobe epilepsies (seven of ten patients, 70 %), one patient had a focal epilepsy originating from temporal (leading to automotor seizures) and frontal (leading to tonic seizures) regions, the other two patients had bilateral focal epilepsies evolving from temporal and frontal lobes. In these patients the seizure pattern of their focal seizures with manual automatisms always started in the temporal lobe, if their seizure originated from the frontal lobe, they had other semiologies (hyperkinetic or versive seizures). The seven patients in whom we recorded hyperkinetic seizures had either frontal (three patients, 43 %) or bilateral focal epilepsies (two bilateral frontal lobe, two bilateral frontal and temporal lobe epilepsies). More detailed information about the analysed seizures is listed in Table S1. The demographic data and overall seizure semiologies of the patients are listed in Table S2.

4.1.2. Movement parameters

4.1.2.1. Main results. Hyperkinetic seizures exhibited a higher mean **velocity** in every ROI (head, left hand, right hand, trunk), as well as higher mean acceleration and mean jerk in most of the ROI, compared to focal seizures with manual automatisms, these differences were statistically significant (Fig. 1A–F, Table 1).

Specifically, the hyperkinetic seizures had a significantly higher mean velocity than the focal seizures with manual automatisms with 0.62 ± 0.28 (m/s) versus 0.12 ± 0.07 (m/s) for the head, 0.61 ± 0.29 (m/s) versus 0.16 ± 0.05 (m/s) for the right hand, 0.68 ± 0.30 (m/s) versus 0.17 ± 0.08 (m/s) for the left hand, 0.47 ± 0.29 (m/s) versus 0.10 ± 0.07 (m/s) for the trunk. With the highest mean velocity of the left hand with 0.68 ± 0.30 (m/s) for hyperkinetic seizures and 0.17 ± 0.08 (m/s) for focal seizures with manual automatisms. While the lowest mean velocity was measured on the trunk with 0.47 ± 0.29 (m/s) in hyperkinetic and 0.10 ± 0.07 (m/s) in focal seizures with manual automatisms.

Furthermore, mean **acceleration** was also significantly higher in hyperkinetic seizures with 3.01 ± 1.65 (m/s^2) versus 0.63 ± 0.52 (m/s^2) for the head, 3.46 ± 1.74 (m/s^2) versus 0.81 ± 0.38 (m/s^2) for the left hand and 2.40 ± 1.56 (m/s^2) versus 0.53 ± 0.40 (m/s^2) for the trunk. After Holm-Bonferroni correction, however, this difference was not significant for the right hand 3.06 ± 1.44 (m/s^2) versus 0.84 ± 0.35 (m/s^2).

Comparing the mean **jerk** (= the third derivative of displacement with respect to time), it was also higher in hyperkinetic seizures than in focal seizures with manual automatisms in all ROI: for the head with 13.64 ± 7.69 (m/s^3) versus 3.39 ± 3.73 (m/s^3), for the right hand with 14.94 ± 8.69 (m/s^3) versus 4.32 ± 2.36 (m/s^3) for the left hand with 19.17 ± 12.69 (m/s^3) versus 3.92 ± 1.93 (m/s^3) and for the trunk with 10.90 ± 6.62 (m/s^3) versus 2.82 ± 2.69 (m/s^3). This difference of the jerk was significant in all ROI, except for the right hand, which after

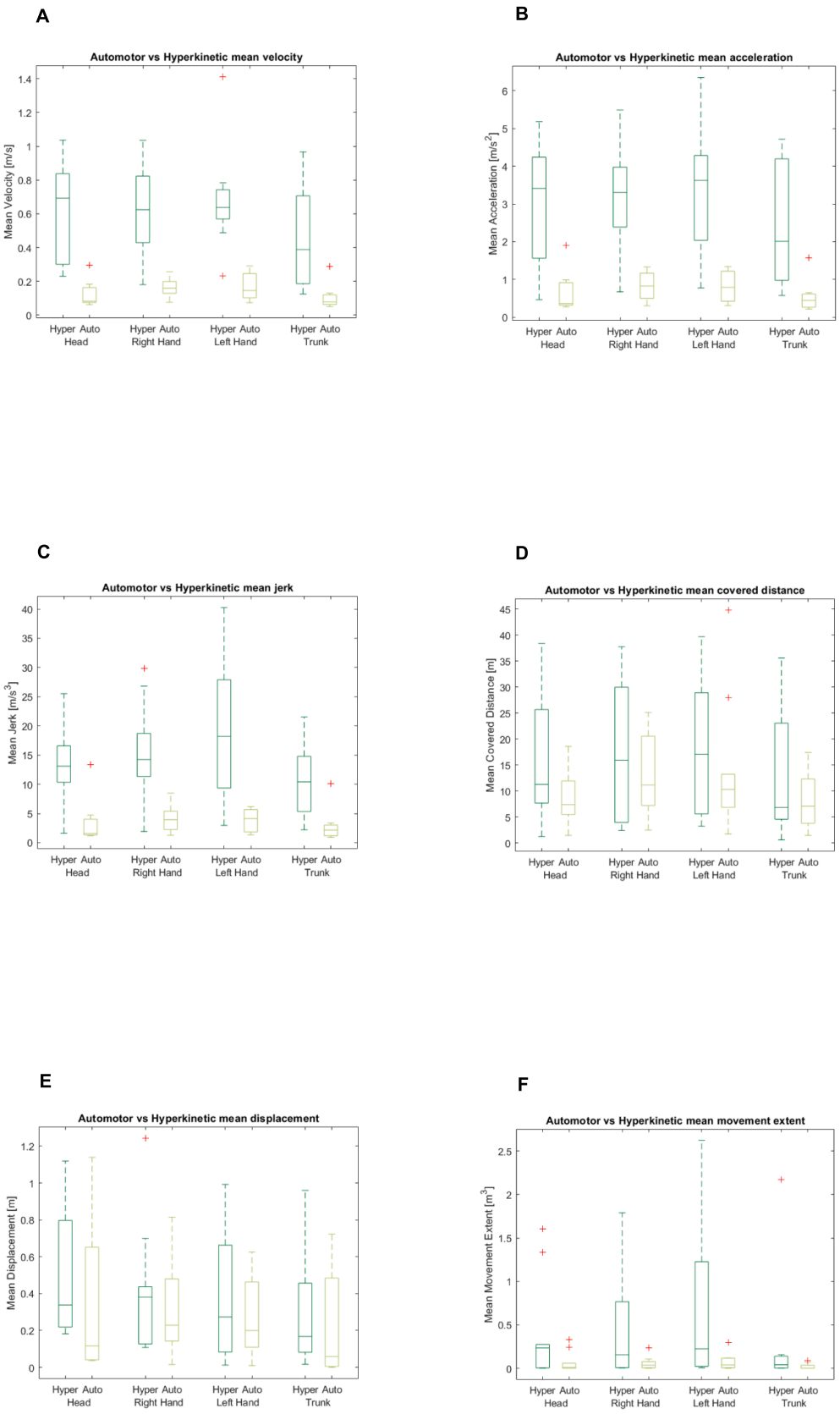

Fig. 1. A-F Mean quantitative parameters in boxplots compared through ROIs (Regions of Interest) of focal seizures with manual automatisms (= automotor) versus hyperkinetic seizures. On each box, central marks indicates the median, bottom and top edges of the box are 25th and 75th percentiles. The whiskers are the most extreme data points, the red "+" markers are outliers.

Table 1
Quantitative comparison of hyperkinetic seizures versus focal seizures with manual automatisms (automotor); bold p-values are statistically significant with Holm-Bonferroni correction (Mann-Whitney *U* test or Wilcoxon rank sum test,) mean values are reported and standard deviation of mean values for velocity, acceleration, jerk.

		Movement quantitative parameters					
		Velocity (m/s)	**p value**	**Acceleration (m/s^2)**	**p value**	**Jerk (m/s^3)**	**p value**
Head	Hyperkinetic	0.62+/-0.28	**0.0003**	3.01+/-1.65	**0.001**	13.64+/-7.69	**0.0028**
	Automotor	0.12+/-0.07		0.63+/-0.52		3.39+/-3.73	
Right Hand	Hyperkinetic	0.61+/-0.29	**0.0006**	3.06+/-1.44	0.0036	14.94+/-8.69	0.0073
	Automotor	0.16+/-0.05		0.84+/-0.35		4.32+/-2.36	
Left Hand	Hyperkinetic	0.68+/-0.30	**0.0004**	3.46+/-1.74	**0.0008**	19.17+/-12.69	**0.0017**
	Automotor	0.17+/-0.08		0.81+/-0.38		3.92+/-1.93	
Trunk	Hyperkinetic	0.47+/-0.29	**0.0006**	2.40+/-1.56	**0.001**	10.90+/-6.62	**0.0022**
	Automotor	0.10+/-0.07		0.53+/-0.40		2.82+/-2.69	
		Covered Distance (m)	**p value**	**Displacement (m)**	**p value**	**Movement Extent (m)**	**p value**
Head	Hyperkinetic	15.88 +/- 11.77	0.162	0.50 +/- 0.34	0.1405	0.41 +/- 0.57	0.1212
	Automotor	8.66 +/- 5.73		0.35 +/- 0.40		0.07 +/- 0.12	
Right Hand	Hyperkinetic	16.94 +/- 13.63	0.6776	0.42 +/- 0.34	0.4727	0.46 +/- 0.60	0.1859
	Automotor	12.89 +/- 8.27		0.30 +/- 0.24		0.06 +/- 0.07	
Left Hand	Hyperkinetic	17.66 +/- 13.12	0.6776	0.38 +/- 0.34	0.5708	0.61 +/- 0.86	0.1212
	Automotor	14.01 +/- 12.98		0.27 +/- 0.21		0.07 +/- 0.09	
Trunk	Hyperkinetic	13.82 +/- 13.01	0.4727	0.27 +/- 0.29	0.3447	0.27 +/- 0.67	0.0452
	Automotor	7.91 +/- 5.41		0.22 +/- 0.29		0.02 +/- 0.03	

Table 2
Average clinical seizure lengths (statistically significant difference).

			p value
Duration of upper limb automatisms (mm:ss)	Hyperkinetic	00:26 +/- 00:14	**0.0011**
	Focal seizures with manual automatisms	01:20 +/- 00:38	

applying the Holm-Bonferroni correction was no longer significant.

4.1.2.2. Secondary results. The mean **covered distance**, mean **displacement** of all ROI and mean **movement extent** of head, left hand and right hand were also higher in hyperkinetic seizures than in focal seizures with manual automatisms but not at a statistically significant level (Fig. 1A–F, Table 1). From the covered distance of the movements (= total path), the displacement (= direct distance from start to end) and movement extent (= maximum range of movement), all tend to have a relatively large standard deviation, still, the movement extent tends to have the lowest p-values, between the two semiologies.

The movement extent of the trunk was numerically higher in hyperkinetic seizures than in focal seizures with manual automatisms (0.27 ± 0.67 (m) versus 0.02 ± 0.03 (m), p = 0.045). Although the uncorrected p-value was 0.045, this did not remain statistically significant after Holm-Bonferroni adjustment. The mean velocity had the lowest standard deviation range (±0.05–0.30 (m/s)), compared to mean acceleration (±0.35–1.74 (m/s^2)) and mean jerk (±1.93–12.69 (m/s^3)), as explained by the way they are calculated in equation (3–5), as these metrics highly correlate with each other (Tab. 1). The mean velocity differences showed the smallest p-values (p = 0.0003–0.0006), compared to mean acceleration (p = 0.0008–0.0036) and mean jerk (p = 0.0017–0.0073), which were mostly significant levels after correction, indicating the strongest statistical evidence for a difference between seizure types, although p-values do not reflect the size of the effect itself. The difference between the mean movement extent with a p-value range of (p = 0.045–0.186), mean displacement (p = 0.141–0.571), and mean covered distance (p = 0.162–0.688) were not significant. Examples of a tracked focal seizure with manual automatisms and a hyperkinetic seizure, respectively, can be found in the supplementary material (S 3, S 4).

4.2. Seizure duration

The mean overall seizure duration (consisting of start and end of the EEG seizure pattern and start and end of the seizure semiology) was longer in focal seizures with manual automatisms than in hyperkinetic seizures (152 ± 135 s vs. 40 ± 18 s, p = 0.019). Still, this difference was not significant after Holm-Bonferroni correction. The mean duration of ictal upper limb automatisms was also shorter in hyperkinetic seizures (26 ± 14 s vs. 80 ± 38 s, p = 0.001, Tab. 2). Upon Holm-Bonferroni correction the difference was still significant.

4.3. 3D visualization

The movement can be tracked in a 3D viewer which allows us to see the movement pattern in space. Fig. 2 depicts the extent of all ROI in a hyperkinetic seizure in comparison to a focal seizure with manual automatisms. The system allows us to visualize a single ROI's MOI pattern in 3D, for instance the left hand pattern of two of our study's patients is visualized (on Fig. 3, comparing the movement pattern of a hyperkinetic to a focal seizure with manual automatisms). The movement of any tracked body part, ROI, can be visualized in 3D space, allowing the movement pattern to be rotated around and inspected from any desired viewpoint (Figs. 2 and 3). Another novel visualization method based on our previous work on quantitative analysis of seizure semiology [25] was introduced creating a velocity graph: the comparison of the velocity graph of a hyperkinetic versus a focal seizure with manual automatisms shows the different distribution and intensity of the movements over time (Fig. 4). With this method from the beginning to the end of the seizure the movement of each ROI is visualized in one figure, for convenient review of the seizure velocity pattern, naturally this type of visualization is applicable for acceleration and jerk as well.

5. Discussion

Current video analysis approaches quantifying seizure movements are utilized only for research studies and not yet implemented in the clinical routine to reduce observer bias and error in seizure diagnosis and classification, which would be a crucial future application of such systems. This study intended to demonstrate a practical system, with 3D quantification and practical visualization techniques, to inspire further quantitative studies, with more complex classes to realize a quantitative epileptic seizure diagnosis support system. The 3D approach presented here for quantifying epileptic movement provides a simple, fast and low-

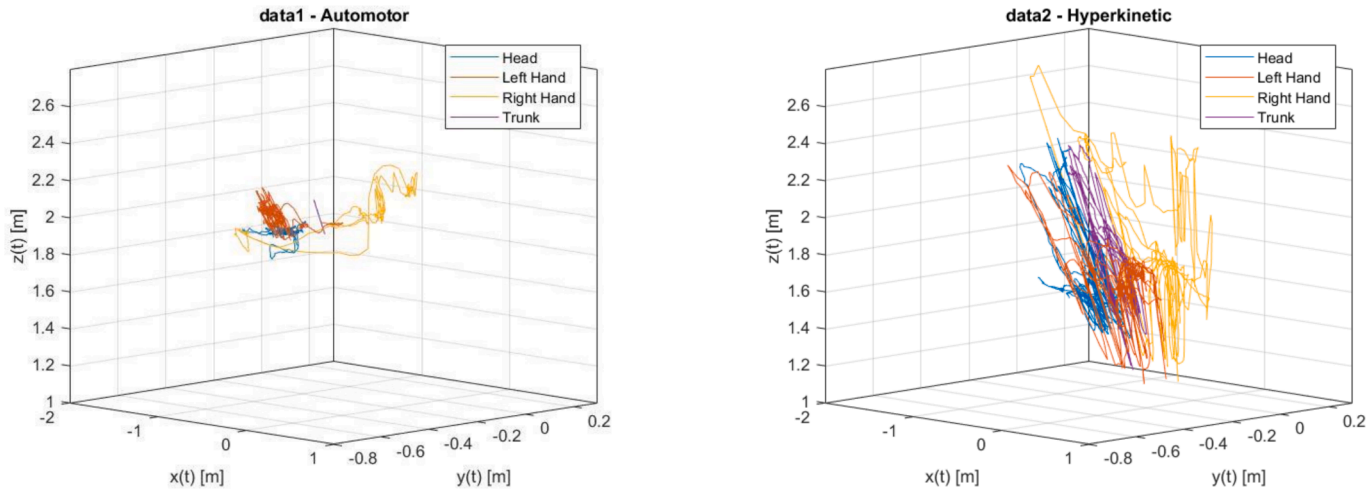

Fig. 2. Focal seizure with manual automatisms (= automotor) versus Hyperkinetic seizure full 3D path of all ROIs (Regions of Interest).

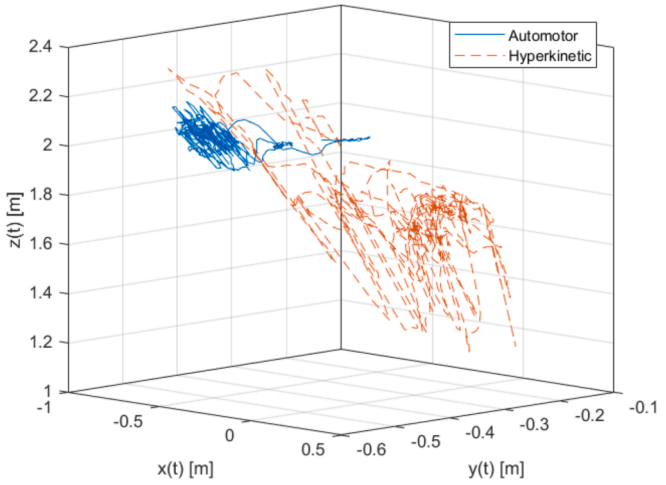

Fig. 3. Hand movement (left hand) path comparison of a hyperkinetic seizure versus a focal seizure with manual automatisms (= automotor), same patients as in Fig. 1.

cost procedure to differentiate seizures characterized by certain ictal repetitive movements. This method provides objective data to differentiate between focal seizures with manual automatisms and hyperkinetic seizures. Objective measures are required because semiological seizure analysis by visual inspection only and eye witness report is prone to high interrater variability [11] and uncertain classification [33]. Earlier studies of our group showed that quantitative movement analysis can add interrater independent objective information to seizure analysis in terms of lateralization and localization [26,27,29,34]. This novel 3-D-approach to quantify upper limb repetitive movement is less limited than our former 2-D techniques. In line with our former 2-D results, this 3-D study confirms that hyperkinetic seizures can be identified by higher mean velocity, mean acceleration and mean jerk as well as by greater covered distance, displacement and movement extent [27,34].

As well established in former studies [35,36] hyperkinetic seizures were highly associated with frontal lobe epilepsies in our patient sample (five of seven patients with hyperkinetic seizures had frontal lobe epilepsies, 71.4 %). The other two patients with hyperkinetic seizures had focal epilepsies with seizures originating from frontal and additionally from temporal lobes (one of them was the patient in whom we recorded both, one hyperkinetic and one focal seizure with manual automatisms). As well established, most patients with temporal lobe epilepsies have focal seizures with manual automatisms [6,37,38]. All our patients with this semiology had seizures arising from temporal lobes. Seven patients had focal seizures with manual automatisms arising from the temporal lobes, three of these patients had also additional seizure types generated from frontal regions. We cannot exclude that the seizure origin of these patients could have been the insula or our other regions since we did not perform invasive recordings in these patients.

The clinical observation that many patients with FLE have seizures with fast movements especially involving the proximal joints [36,39] could also be observed in our study as the trunk is mainly involved. However, we must note that here we only examined the trunk and hands. A more granular analysis of the movements, from proximal to distal, would require the inclusion the shoulders and elbows. This clinical finding that the movement in hyperkinetic seizures takes place mostly in the proximal part of the body may help explain why the trunk movement extent showed an uncorrected p-value below 0.05, though the observed effect did not reach statistical significance after the Holmes-Bonferroni correction. The standard deviation of the right and left hand being higher than of the head or the trunk might be due to the fact that we took seizures from as many different patients as possible. Some seizures involved movement of the right hand, some of the left hand, others of both hands. Thus, when calculating the average metric of one of these ROIs which in some seizures includes non-movement of one limb and in other seizures large movements of that limb, will naturally result in high standard deviation. This is in line with the observation that especially in temporal lobe epilepsy patients, seizures frequently present asymmetric arm movements (contralateral unilateral hand dystonia and ipsilateral hand automatisms) [40].

This study corroborates previous studies including our 2D-analysis [27], that the total seizure duration in focal seizures with manual automatisms is longer than in hyperkinetic seizures [11,26,36]. Additionally, the mean duration of the ictal upper limb automatisms was also significantly longer in focal seizures with manual automatisms than in hyperkinetic seizures in this study (80 ± 38 s vs 26 ± 14 s). This differs from similar median duration described by other authors (TLE mostly focal seizures with manual automatisms (26 ± 17 s) and FLE mainly hyperkinetic seizures (27 ± 14 s) [27]). This might be related to the limitation of the former 2D technique, where movements perpendicular to the camera angle might have been missed.

5.1. *The visualization advantages and clinical opportunities*

As a new approach to visualize movement in epileptic seizures, our figures demonstrate that it is now possible to review the three-dimensional pathway of each ROI and to compare them with each other. Fig. 2 and Fig. 3 are representing interactive 3D figures, which

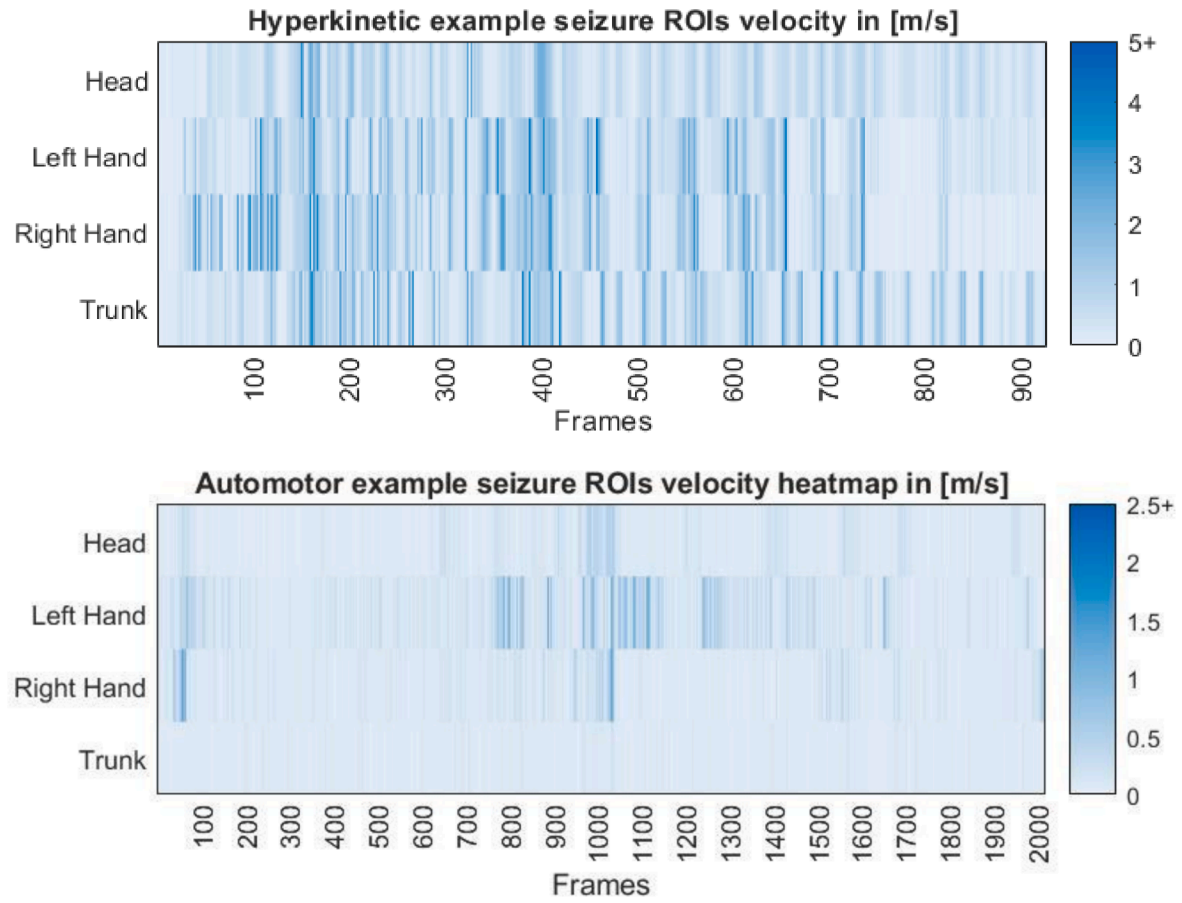

Fig. 4. Velocity graph of a hyperkinetic and a focal seizure with manual automatisms (= automotor).

could be moved around during the analysis to see the movement from different angles, which facilitates the full understanding of the extent of movement in space. Movement that was previously lost in the two-dimensional analysis is now captured and can be incorporated into the analysis (Fig. 3). As Fig. 4 visualizes the seizure velocity pattern over the entire seizure duration it transforms 3D data over time into a 2D figure, which can be a helpful tool to compare different seizure types. This kind of visualization technique can be applied to visualize other movement parameters such acceleration in jerks as well.

This system overcomes major limitations of our previous 2D marker-based system using a monochrome camera and infrared markers attached to the patient's body. As here in the study, different parts of the body and different viewpoints of the movement can be visualized in 3D and analysed to provide a more accurate analysis of the movements.

5.2. Limitations

The technique has some limitations. It may require considerable manual effort of marking and tracking of the ROI, if the system loses track of the ROI from optical flow-based tracking. Additionally, when the background and the tracked ROI are in close interaction, the depth criteria might fail, thus confusing the ROI with the background image. This makes it time-consuming and might render it difficult to integrate it into the clinical routine of an EMU.

Recording the seizure including the depth video stream requires the initial purchase and installation of dedicated camera equipment that is not part of the usual recording platform for regular epilepsy monitoring units (EMU). Additionally, this technique continues to be restricted to specialized units that possess the infrastructure and computational capacity required to store and process such extensive volumes of data.

Some differences in our results section may be clinically relevant, but because of our relatively small number of seizures, they may not reach statistical significance. This quantitative approach could be expanded to a greater patient sample and to other seizure types. Due to 24/7 monitoring in the EMU only relatively low-resolution IR-D data was available from the NeuroKinect dataset, thus, this tracking algorithm was a preferable option to any RGB based ones. There was a significant difference in the movement metrics between the two seizure groups but to automatically discriminate between them it would require the application of predictive models or machine learning techniques, as we describe in our previous study [15]. Such an approach is necessary also to validate the method's classification accuracy especially when HD-RGB data is available, which we are actively working on, collecting a large HD-RGB dataset for future follow up works [41].

We included only patients that were >18 years old to have a comparable population. As the individual's body shape and size varies and our application uses Cartesian space with absolute values of movement distance it may lead to misinterpretation when the subject's physical stature significantly deviates from the median demographic of the study population. In the future this could be addressed with some type of normalization based on the body shape, for example by height of the patients, or even by bone lengths.

Fine finger movements that also occur in manual automatisms and facial expression (e.g. oral automatisms) are features analysed by visual assessment of seizure semiology are not captured in the currently presented method. This is due to the limited resolution, and lack of detailed RGB features of the video recordings, however in this study this is an expected trade-off to utilize at night monitoring clinical videos as well.

6. Conclusion

Our study shows that this technical setup can be used in the clinical

routine of a standard EMU and allows visualization and quantitative analysis of ictal automatic movements. It allows the quantitative discrimination between seizures characterized by movements such as focal seizures with manual automatisms and hyperkinetic seizures. Yet the gold standard of seizure analysis is visual inspection by a human which has high interrater variability. For our study we only chose seizures with clear automatisms and hyperkinetic movements. Still, our method is dependent on the evaluation against the gold standard, the aim of future works would be to find a threshold of the quantitative movement parameters that are even visually hard to differentiate, such as, complex motor seizures with impaired awareness, and have them automatically classified.

Future work should evaluate this method in an unselected patient group with all different kinds of epileptic motor seizures and should reduce the required effort for the observer.

7. Written informed consent

Written informed consent was obtained from all participants (or guardians of participants) in the study.

Ethical publication Statement

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

The study was approved by the ethics committee of the University of Munich (ethical approval number: 217–13).

CRediT authorship contribution statement

Anna Mira Loesch-Biffar: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tamás Karácsony:** Writing – review & editing, Writing – original draft, Visualization, Software, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Leah Sattlegger:** Formal analysis, Data curation. **Christian Vollmar:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Jan Rémi:** Writing – review & editing, Data curation, Conceptualization. **João Paulo Silva Cunha:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation. **Soheyl Noachtar:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.yebeh.2025.110486.

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