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PEOPLE WITH LOW BACK PAIN SHOW REDUCED MOVEMENT COMPLEXITY DURING THEIR MOST ACTIVE DAILY TASKS

Short title: Chronic low back pain reduces movement complexity

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Significance:

People with chronic pain move differently. Movement quality is difficult to evaluate during daily activities, yet it may prove more informative than quantitative measurements.

We proposed a new approach for computing movement complexity and found out that patients' movements get more stereotyped when higher spinal acceleration is required.

Abstract

Background: Actigraphy is a quantitative method for the investigation of human physical activity and is normally based on accelerometric and/or kinematic data.

Methods: A multichannel actigraphy system, able to record both acceleration and spine angles, was employed in this study to measure the quality of movement in 17 individuals with chronic low back pain (LBP) and 18 healthy individuals during unrestricted daily activities. An indication of movement complexity was computed by means of non-negative matrix factorization throughout the 24 hours period and in the 60 minutes of highest activity.

Results: Movement complexity differed only when the 60 minutes of highest activity were taken into account, with the LBP group showing reduced complexity (e.g. for dimensionality = 8, over 90% of the comparisons showed a significant reduction in the LBP group).

Conclusions: The results are compatible with the hypothesis that pain induces a reduction of the available kinematic trajectories and degrees of freedom during natural movements, which becomes more evident when more demanding tasks are performed.

A reduced movement complexity suggests a persistent alteration of the descending neural pathways and/or a disrupted somatosensory information processing, which could be possibly contrasted by administering highly variable motor tasks.

Introduction

People with low back pain (LBP) move differently. Due to the heterogeneity of individuals' daily activities (e.g. working habits, training), movement quantification may not suffice at describing the motor consequences of pain. The *quality* of movement, on the other hand, may be a more promising indicator of ongoing neuromuscular dysfunction in people with chronic pain (Falla & Hodges 2017)

It was recently shown that movement quality changes in people with LBP during the performance of a repetitive task from a kinematic (Dideriksen et al. 2014)and neural (Falla et al. 2014) perspective. People with chronic spinal pain also exhibit an altered repertoire of movement during locomotion (Falla et al. 2017; Lamoth et al. 2006) or cued arm lifting (Jacobs et al. 2009) – even whilst in remission of symptoms.

Movement complexity and variability are reduced in people with chronic pain: whilst it may prove to be immediately beneficial (e.g. to avoid pain provocation) the long-term consequences may be harmful, leading to perpetration or recurrence of pain (Crombeza et al. 1999; Hodges & Tucker 2011). These conclusions, however, were drawn from studies typically performed under laboratory conditions and a detailed analysis of movement quality during daily activities is, at present, unavailable.

Actigraphy is a quantitative method for investigating human physical activity, based on accelerometric and/or kinematic data. It can be used as an inexpensive, portable alternative to polysomnography [19] or to quantify the amount of movements performed during one day. Wrist or belt-worn actigraphic devices, however, lack precision in determining the phases of sleep (Brage et al. 2003; Brooks et al. 2005; Chen et al. 2003), are not capable of quantifying energy expenditure during daily activities (Hargens et al. 2017) and generally provide only rough computations (e.g. movement counts or integral acceleration) (Kosmadopoulos et al. 2014). New multi-modal systems, able to record kinematic data over long periods of unrestricted activity, have been recently developed (Taylor et al. 2010), and their full potential has yet to be explored.

A recently developed system (Spine, Epionics Medical GmbH, Postdam Germany, Figure 1) was used to measure human spinal movements in laboratory conditions (Consmüller et al. 2012; Dideriksen et al. 2014; Rohlmann et al. 2014; Taylor et al. 2010) and over a 24 hours period (Rohlmann et al. 2014). Rohlmann and colleagues, for example, report that in healthy individuals the majority of movements spans a relatively small range of motion (5° to 10°) with a limited amount of time (<2%) spent in lumbar extension over 24 hours.

Recent studies (Bauer et al. 2017; Dideriksen et al. 2014) conclude that people with LBP show a less complex movement repertoire compared to their healthy counterparts in laboratory conditions. Movement complexity is traditionally investigated by computing determinism (%DET) or sample entropy. An indirect measure of complexity can be obtained by means of non-negative matrix factorization, which allows robust estimations irrespectively of the absolute value of the data (Lee & Seung 1999). The term non-negative matrix factorization (NMF) describes a family of unsupervised learning algorithms that reduce the dimensionality of a dataset (Lee & Seung 2001) and enhance sub-structures, clusters and hidden regularities (Ding et al. 2005). Differently from classical techniques, which require a priori settings of measurement parameters (e.g., the embedding dimension, or radius threshold) NMF relies on no assumption about the statistical dependencies of the investigated components, and only imposes the constrain of non-negativity (Lee & Seung 1999).The number of components and the quality of reconstruction of the original data through can be used as an indirect measure of its complexity (Giuliani et al. 2001).

The aim of this study was to characterize movement complexity in a cohort of people with non-specific LBP and aged-matched healthy individuals during the performance of unrestricted daily activities over a 24 hours period. We applied a multi-sensor actigraphic device to continuously capture thoracolumbar and lumbar spinal movement and utilized NMF to quantify its complexity.

Methods

Subjects

Seventeen adults presenting with chronic non-specific LBP volunteered for this study.

Participants with LBP with age 18-50 years were recruited through a flyer from general practitioners and physiotherapists, or advertising in the press. Participants were screened for non-specific (i.e., not attributable to a specific pathology recognizable with the data at hand) low back pain at the Pain Clinic of the University of Göttingen. They were included if presented LBP for more than three months with periods of symptom aggravation and remission in the last six months.

Eighteen asymptomatic individuals with comparable age and gender, were recruited to act as the control group. Pain-free participants were included if they had no relevant history of back and/or lower limb pain or injury that limited their function or required treatment.

Participants were excluded if they reported major neurological, respiratory, circulatory, disorders, recent, current or suspected pregnancies, history of spinal surgery or they were undergoing treatment for LBP from health care providers at the time of the measurements and/or if they were involved in specific training programmes targeting LBP. Participants were also excluded from both groups, if they were taking medication such as opioids, anticonvulsives, antidepressants or regularly high dosed non-steroidal anti-inflammatory drugs (NSAIDs). Initial screening was accomplished through phone interviews and eligible participants attended a baseline evaluation appointment. Both groups were asked not to take NSAIDs from the evening before the beginning of the 24 hours recording and throughout the measurement.

Ethical approval for the study was granted by the Ethics Committee of the University of Göttingen, and the procedures were conducted according to the Declaration of Helsinki. Measurements were performed at the Department of Neurorehabilitation Engineering, Göttingen, Germany.

Questionnaires

All participants completed questions on their demographics and completed the SF-36 Health Survey (McHorney et al. 1994), to measure their general mental and physical health status.

The participants with LBP were also requested to complete a series of questionnaires to obtain information on their LBP history. In addition the State scale of the Spielberger State-Trait Anxiety Inventory (STAI)(Short Form) was completed to assess anxiety (Spielberger et al. 1983). The

Oswestry Disability Index (ODI) (10 items)(Baker et al. 1989) was used to assess pain-related disabilities associated with LBP. The Tampa Scale for Kinesiophobia (TSK; 17 items) (Vlaeyen et al. 1995), was used to assess fear-avoidance behavior and fear-avoidance beliefs. Finally, they completed the Pain Catastrophizing Scale (PCS)(Sullivan et al. 1995) to assess catastrophic thinking related to pain.

Activity diaries

Participants were requested to fill activity diaries during the 24 hours of recording, indicating the tasks they were performing throughout the day. They were encouraged to fill the diary continuously throughout the monitored period, but received no specific indications on how to describe their activities; subjects were also asked to refrain from exceptional activities such as (but not limited to) harder-than-usual training sessions.

Diaries were analyzed with a 30 minute resolution and the reported activities clustered in eight numbered categories, derived from those most commonly reported in the diaries (namely: -1: Sleeping, 0: Sitting, 1: Walking, 2: Bike riding, 3: Standing, 4: Eating, 5: Lying - not sleeping, 6: Other, x: Undocumented). In case of periods with multiple reported activities (e.g. working while sitting and standing) the amount of time was weighted equally across activities (e.g. 50% of the time sitting, 50% standing). Percentage (mean ± standard deviation) for each activity was computed and compared across groups.

Actigraphic data collection

Spinal motion was detected using Epionics SPINE (Epionics Medical GmbH, Potsdam, Germany), which provides a temporal assessment of back shape and relative position of the thoracolumbar and lumbar regions. The system has been previously described in detail elsewhere

(Consmüller et al. 2012; Vaisy et al. 2014). Briefly, two flexible sensor strips are fixed paravertebrally to the spine using custom plasters (Figure 1). Each sensor strip measures angles in 12 pre-determined, adjacent, 25-mm long segments fixed lateral to the spine of the subject. Each strip assesses the curvature of the back shape along the 12 connected segments by measuring bending of the segments in the sagittal plane relative to one another using a series of strain gauge sensors. The two sensor strips together are used to quantify movements and rotations outside of the sagittal plane. The system measures relative segment angles at a sampling frequency of 50 samples/s. The position of the sensors was standardized paravertebrally, with each plaster positioned ~5 cm from the mid-sagittal plane. In the vertical direction, the device was also standardized by placing the caudal sensor segment over the level of the posterior superior spina iliaca. Three-dimensional accelerometers are located at the lower and upper ends of each sensor strip, and allow the detection of the sensor's orientation in relation to the earth's gravitational field. The validity and reliability of the measurement tool has been established previously (Consmüller et al. 2012).

Daily activities

Participants were equipped with the measurement system before starting the 24 hours recording session; once the system was fitted and set to record for 24 hours consecutively, they were free to leave the laboratory and were encouraged to engage in their routine activities. Prior to the start of recording, they were requested to stand quietly for a few seconds and baseline data was recorded and stored on the portable system. Participants were asked not to remove the system until the next day, when they returned to the laboratory. At that time, the system was removed and data transferred to a computer hard drive for further analyses.

Actigraphic data processing

Raw data was exported from the EPIONICS proprietary software. All further processing was performed with custom-written Matlab code (Matlab 2017a, The MathWorks, Inc., Natick, Massachusetts, United States). Angles from quiet standing were subtracted from the 24 h data to remove baseline levels related to variation in upright posture and the resulting data was band-pass

filtered (second-order Butterworth bandpass filter, between 0.5 and 12Hz) (Najafi et al. 2003).

Movement complexity

The complexity of movement was tested by comparing the original angle signal with its sparse representation, obtained by means of NMF. For the NMF, a data matrix $X(k)$ (*m* rows, each one representing the output of one sensor, and *p* columns, each one representing a time sample) is normalized to obtain unitary variance and a set of two random matrices S and P(k) is initialized. The NMF algorithm iteratively applies Euclidean multiplicative rules (Lee & Seung 2001) which aim at minimizing the norm of the matrix $\| X - SP \|$ so that the product of the two matrices effectively represents the original data (see eq. 1),

$$X(k) \approx X_r(k) = S \cdot P(k), \qquad (1)$$

where *Xr(k)* is called the 'reconstructed matrix' and represents an approximation of the observed matrix *X(k)*. The dimension of *Xr(k)* are the same as *X(k)*, whereas the dimension of *S* and *P(k)* are *m x n* and *n x p*, respectively, *with n* being the a priori chosen dimensionality of the dataset. The reconstruction quality is assessed by means of the Variation Accounted For (VAF) index, defined as *VAF = 1 − SSE/SST*, where *SSE* (sum of squared errors) is the unexplained variation and *SST* (total sum of squares) is the total variation of the data (Clark et al. 2010; Gizzi et al. 2011; Oliveira et al. 2014). Given a certain dimensionality, the variation accounted for will be higher, when the information shared across the rows of the matrix *X(k)* is high. In other words, given a certain dimensionality, the higher the variation accounted for, the lower is the information cumulatively contained in the signal.

Since the dimensionality of the investigated dataset is not known a priori, the number of modules extracted by NMF ranged between 1 and 12 (see below); in order to minimize the effect of random starting matrices, the analysis was repeated 5 times and the average VAF value was retained for each dimensionality (Muceli et al. 2010; Gizzi et al. 2015).

Movement complexity was computed for both the entire 24 hour period and a representative sample for the 60 minutes that showed the highest activity. For the 24 hour period, absolute angle

data from each side was interpolated in 10 s intervals, resulting in a 12x8640 points matrix, which was submitted to the NFM algorithm.

The 60 minutes of highest activity were identified as follows: the integral of the absolute value of acceleration was evaluated on a 1-minute basis (non-overlapping 3000-samples windows) and the indices of the 60 highest values were retained. Unfiltered angle data, marked belonging to the minutes of highest activity, was concatenated, filtered (second-order Butterworth bandpass filter, between 0.5 and 12Hz) and then interpolated (Gizzi et al. 2015) such that each minute would be represented by 400 samples (24000 samples in total). Finally, data were rectified and submitted to the NMF algorithm. The complexity of movement was measured separately for the left and right side (12 sensors each).

Statistical analysis
Data was tested for normality via the Kolmogorov-Smirnov test. The test revealed a non-normal distribution for all the variables investigated; the two populations are assumed to be independent on each other, therefore the non-parametric Wilcoxon–Mann–Whitney test was used to detect differences between the two groups. For the statistical tests, the significance level was set to $p < 0.05$. To compare the movement complexity across groups, the results were systematically randomized (2^{18} comparisons) and the VAF values tested for significance. The average p-value and the percentage of significant comparisons were retained.

The correlation between questionnaires answers and movement complexity was tested following a similar scheme: the VAF from the two sides was randomized (2^{17} iterations), the R^2 value was computed and its average value was reported. The false discovery rate test from Benjamini, Krieger and Yekutieli (Benjamini et al. 2006) was used to determine the amount of valid comparisons.

Results

Participants

Detailed information (mean ± standard deviation) about the participants is reported in Table 1. The participants with LBP and control subjects did not differ in age, height, weight or gender (P>0.05). However, those with LBP did report lower score for the physical summary scale of the SF-36; P<0.05 but comparable psychological values), which is in line with mild to moderate low back pain with little psychological comorbidity. The average score on the ODI was 14.2 ± 7.2 indicating that the LBP group had relatively mild pain-related disability. The LBP group had pain on average for 34.2 ± 29.3 months.

Diaries

One individual with LBP and one control did not complete their diaries. According to the digitized diaries, the LBP and control groups spent similar amounts of time in most of the examined activity categories (Table 2). Except for one participant with LBP, none reported explicitly the activity of "standing" (Table 2). The only significant difference was in the time reported as "undocumented" (p = .026): those with LBP did not document ~13% of their time, whilst controls did not account for ~4% of their time.

Across the 24 hour period, people with LBP and asymptomatic controls reported similar amounts of resting (i.e. sleeping and lying down without sleeping) (30.76±9.97% vs 31.86±6.62%; p = .93, and 0.74±1.59% vs 0.86±2.38% p = .779, respectively).

Actigraphic data: movement complexity

The comparison of VAF over the 24 hours revealed no differences in the complexity of movement between groups, with no observed significance (on average) across the 12 dimensions explored. In the best- case scenario (dimensionality = 8) the comparison resulted statistically significant in less than 28% of cases Figure 2, left).

However, when only the 60 minutes of highest activity were taken into account, the two

groups showed significant differences in 8 out of 12 dimensionalities; there were 5 cases in which more than 80% of the randomized comparisons were significant. Once again, the dimensionality with the strongest significance (and the highest percentage of significant comparisons) was 8 (P = 0.024 and 91.88% of significant comparisons, respectively, cf. Table 3 right and Figure 3. The false rate discovery test indicated that 98 to 100% of those comparisons could be considered valid.

The correlation between questionnaires and motor complexity was very weak (STAI, catastrophizing, TSK), to weak (ODI) (the first value refers to the 24 hours analysis, the second to the 60 minutes): STAI = [0.045; 0.018], catastrophizing = [0.012; 0.02], TSK = [0.006; 0.01], ODI = [0.261, 0.247]).

Discussion

We analyzed the movement complexity in a cohort of people with non-specific LBP and a group of age-matched healthy controls. The complexity of movement was lower for the LBP group, but only when the time with the highest activity was considered.

Interpretation of the results

Diaries show that the presence of chronic LBP does not generally impair daily activities (i.e., that the LBP group daily activities are comparable with their asymptomatic counterparts). However, when the quality of movement was taken into account, differences emerged: the LBP participants tend to move more stereotypically, as testified by the higher amount of VAF for the same dimensionality. The difference is evident, however, only when the most active phase of their activities are considered.

These results could be interpreted in different ways: either the most active tasks caused discomfort (although, too light to be reported) that immediately altered their movement strategy, or the history of their LBP caused a stable alteration of the motor strategies, which became more evident when the most demanding tasks were performed. Whilst for the first case, it appears at least unlikely that the

entire cohort (17 people with LBP) failed to report any pain, for the second case a large body of literature indicates that the fear of pain may also change motor strategies which persists in the absence of symptoms (Crombeza et al. 1999). This is consistent with the mild to moderate score in the TSK questionnaire of our LBP group. The altered motor strategies, may be caused by a series of disrupted descending commands and/or an altered influence of somatosensory information on motor control (Mailis-Gagnon et al. 2003; Backonja 1996).

Studies examining movement during repetitive tasks (Madeleine et al. 2008; Dideriksen et al. 2014; Falla et al. 2014) have reported decreased movement variability in people with chronic LBP. The absence of an explicit validation for movement classification of the Epionics SPINE system utilized in the current study impedes a direct comparison of the most intense activities in the two groups, but the results from the diaries suggest that none of the volunteers involved in this study underwent extreme or unconventional actions. New measurements on specific tasks in controlled environments may help in the future to build automatic labeling strategies and overcome the uncertainties related to self-reported activities.

Methodological considerations
The data available for this study is limited to 24 hours of continuous recording. Whilst this is a remarkable amount of information (about 4.3 million samples per channel) it is also true that, despite rare cases, the activity of one day may not be sufficient to represent the usual activity of a given individual. Moreover, our LBP sample had relatively mild disability and different results may be expected in those with higher levels of pain severity or greater disability.

During our experiments the participants were asked not to perform exceptional activities (e.g. training harder than usual) and were requested to report their activities on paper diaries. The analysis of diaries did not reveal any unusual documented activity, yet a longer time span for recording (e.g. one week) would be auspicable for future research.

VAF is not *per se* an indicator of signal complexity and, therefore, it is not possible to directly

correlate our results with direct measures such as sample entropy or measures of determinism/ chaoticity (e.g. %DET). The NMF output, however, represents a sparse version of the original signal as linear combination of bases (Lee & Seung 1999). The presence of features that are not shared across channels results in a higher dimensionality for a target minimum quality of reconstruction (VAF) or as a decreased quality of reconstruction for the same dimensionality. We adopted the second criterion because it is more sensitive to the small differences that may have appeared between the two groups.

Conclusion

Despite similar reported activities, people with chronic LBP show a reduced complexity of movement during the most intense part of their day. This is compatible with the hypothesis that pain induces a reduction of the available kinematic trajectories and degrees of freedom during natural movements, and that this is more evident when more demanding tasks are performed.

The fact that movement complexity is reduced in people with LBP despite the absence of perceived pain suggests a persistent alteration of the descending neural pathways and/or a disrupted somatosensory information processing, which could be possibly contrasted by administering highly variable motor tasks.

Conflict of interest

The authors declare no conflict of interest.

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Tables

Table 1. Participants' anthropometric data and questionnaires scores. ODI: Oswestry Disability Index (Baker et al. 1989), SF-36: SF-36 Health Survey (McHorney et al. 1994), TSK: Tampa Scale for Kinesiophobia (Vlaeyen et al. 1995), PCS: Pain Catastrophizing Scale (Sullivan et al. 1995), STAI: Spielberger State-Trait Anxiety Inventory. Bold values indicate a significant difference.

	Mean		SD	
Anthropometrics	Controls	Patients	Controls	Patients
Age (yrs)	29.7	32.5	7.3	9.2
Gender (%female)	53	58		
Height (cm)	174.8	177.0	10.3	11.5
Weight (kg)	69.2	76.3	14	11.5
Duration of pain (months)		34.2		29.3
ODI (0-100%)		13.9		6.8
Physical Summary Score (0-100)	**54**	**44.8**	3.3	8
Mental Summary Score (0-100)	46.1	44.4	5.8	8.4
TSK (17-68)		32.1		7.1
PCS (0-52)		14.2		9.4
STAI (20-80)		40.8		8.2

Table 2. Diaries results in the two groups, data is reported as p-value, Mean and standard deviation (SD). LBP: Low Back Pain

Diaries analysis		Mean %		SD %	
	p-value	Controls	LBP	Controls	LBP
Sleeping (%)	0.93	31.86	30.76	6.62	9.97
Sitting (%)	0.397	23.65	16.91	18.27	10.13
Walking (%)	0.787	3.19	2.70	6.67	4.33
Biking (%)	0.854	3.55	3.06	4.89	3.86
Standing (%)	0.346	0.00	1.23	0.00	4.90
Eating (%)	0.482	4.53	4.04	4.59	5.91
Lying (%)	0.779	0.86	0.74	2.38	1.59
Other (%)	1	27.57	27.57	17.73	16.60
Undocumented (%)	**0.026**	4.78	12.99	6.42	15.27

Table 3. Complexity analysis for the movement of the two groups across the 24 hours (left section) and the 60 minutes of highest activity (right section). Data is reported as percentage of valid comparisons, the percentage of significant comparisonsP-values, average p-value from the whole pool of comparisons and average VAF for both groups. Average significant p-values are reported in bold.

| | 24 hours | | | | | 60 minutes | | | | |
	% Valid	% <.05	avg P	avg VAF Controls	Patients	% Valid	% <.05	avg P	avg VAF Controls	Patients
Dim										
1	0	0.59	0.288	0.6162	0.6579	0	15.60	0.206	0.5367	0.5715
2	0	13.08	0.175	0.7216	0.7579	0	54.77	0.069	0.6710	0.7115
3	0	11.01	0.176	0.7881	0.8168	0	71.51	**0.042**	0.7568	0.7943
4	0	9.67	0.191	0.8357	0.8598	0	69.79	**0.043**	0.8185	0.8500
5	0	9.29	0.167	0.8709	0.8917	98	80.83	**0.032**	0.8616	0.8896
6	0	15.03	0.143	0.8987	0.9166	100	91.03	**0.023**	0.8948	0.9193
7	0	23.96	0.105	0.9229	0.9374	100	90.44	**0.024**	0.9217	0.9415
8	0	27.71	0.090	0.9426	0.9548	100	91.88	**0.024**	0.9434	0.9589
9	0	12.18	0.135	0.9612	0.9690	100	86.95	**0.029**	0.9627	0.9733
10	0	1.72	0.263	0.9775	0.9810	0	56.86	**0.056**	0.9776	0.9833
11	0	0.00	0.762	0.9899	0.9904	0	14.23	0.173	0.9888	0.9904
12	0	0.46	0.318	0.9985	0.9975	16	43.12	0.155	0.9966	0.9950

Figures
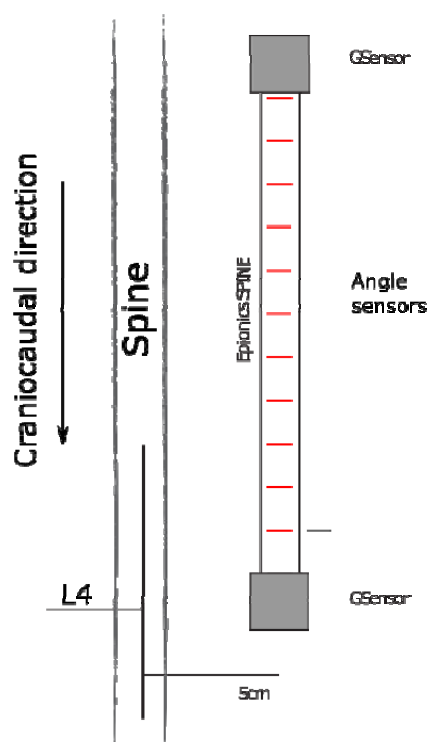
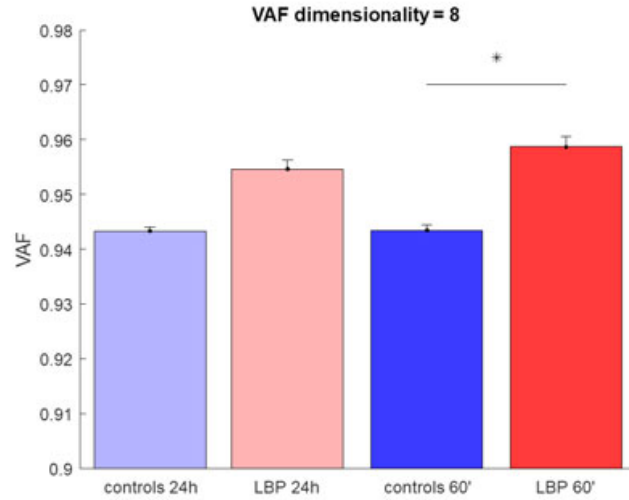*Figure 1. Graphical representation of the sensors' placement. The left-side sensors strip is omitted*

Figure 2. Average variation accounted for in the controls (shades of blue) and patients (shades of red) for the entire 24 hours period (left) and the 60 minutes of highest activity (right)
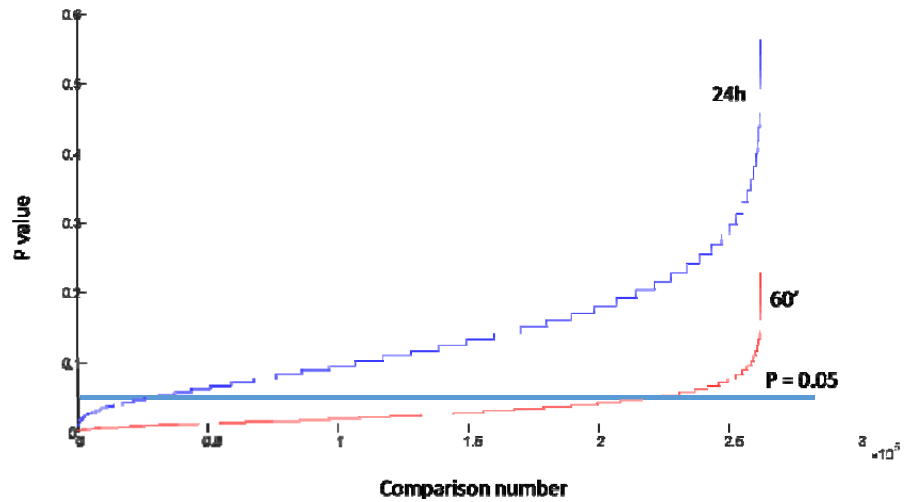

Figure 3. Representation of the significance (p-value) of the systematic comparison (about 2.6*10^5) for a dimensionality of 8. Data is reported in ascending order. It is worth noting that for the 60 minutes analysis the percentage of significant comparisons was much higher than in the 24 hours case.