A Closed-Loop System for Real-Time Calibration of Neural Stimulation Parameters using Motion Data

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***Abstract*— The vision behind our project is a closed-loop system for continuous deep brain stimulation (DBS) based on features extracted from complex motion data. Our focus is on Parkinsons Disease (PD) patients, with a possible expansion to related neurological disorders. The system we envision is lightweight, will continuously gather motion information, will automatically extract high-level features from this data in real-time, and will feed back this information to continuously calibrate the parameters of a deep-brain stimulation (DBS) electrode.**

I. Motivation

Neuromodulation devices such as DBS provide targeted electrical stimulation to treat motor symptoms, e.g., in Parkinsons disease, essential tremor, and dystonia. Currently, state of the art DBS requires not only accurate placement of the stimulating electrode within the neural tissue, but also appropriate selection of stimulation parameters, e.g., amplitude, pulse width, and frequency [1]. These parameters can also be used to alleviate unwanted side effects including hemiballism, gait and speech disturbances, and dyskinesias [2]. While many patients benefit from DBS, the parameter selection process is still largely empirical, and recalibration sessions may be weeks or months apart, which is not ideal as the disease progresses over time.

II. Approach

Within this project we are addressing the following main goals and challenges. First, we want to bring our already developed motion feature extraction to the level necessary for closing the loop. This will involve considering high-level across-motion features (e.g., smoothness and jerk), as well as complex feature correlations. We also need to automate the (so far manually done) temporal segmentation of the motion data, which splits the data into blocks of the same motion primitives. Second, our envisioned closed-loop system requires motion analysis in real-time. Given the large amounts of data, this requires a careful design and engineering of our basic data structures and extraction algorithms. Third, PD patients are frail and, in advanced stages of the disease, do not tolerate a long dress up and calibation phase to setup the motion capture recordings. In order to minimize the system setup time experience has been gathered in previous work [3]. Finally, we will employ these developments and insights to actually close the loop and provide continuous feedback to a DBS electrode. In a first step, we will extend our toolbox to suggest DBS parameter values to the operator in a DBS calibration session with a patient. We will evaluate these suggestions over many sessions. The ultimate goal for our system is to continuously regulate the DBS signal in accordance with the patients current state of disease as mirrored by his or her current motion pattern and behavior.

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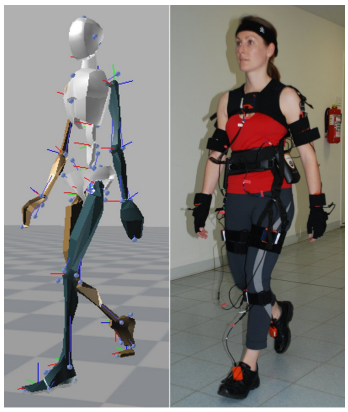

Fig. 1. Whole-Body motion capture using the XSens MVN system.

III. Related Work

Effort has been applied for more than a decade to build automated systems that use patients clinical state to adjust stimulation parameters [1], thereby reducing the delay between stimulation updates by many orders of magnitude as compared to human intervention. These systems require development of sensors to measure patient data and algorithms to translate the data to the appropriate stimulation parameters [4]. Because of the complexity of the nervous system, it is necessary to divide this process into two steps: one that translates sensor data into estimates of patients state (i.e., feature recognition algorithm) and another that translates the state estimate into a stimulation parameter update (i.e., a control policy algorithm). In our project we start out by optimizing the feature recognition process before we target the control policy algorithm. From previous research in [5], [6] it has been suggested that noise in the movement information

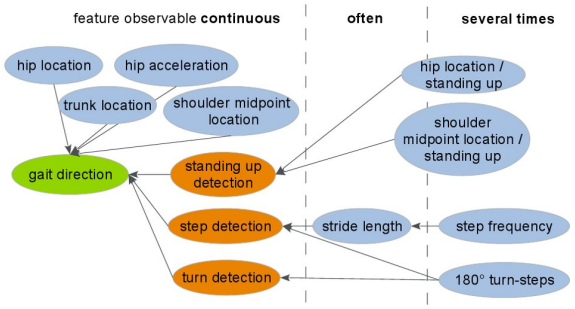

Fig. 2. Low-level features.

can be a key factor that induces patients to change their motor behavior and movement strategies to cope with the disease. We are interested in investigating this concept further to develop a movement driven feedback control for DBS to carefully provide the necessary stimulation to help the patients restore their everyday motor function performance and quality of life.

IV. Clinical Experiments

So far, we investigated four complimentary movement classes, which included: voluntary lean and postural control (functional reach task), gait (10m-walk and Timed-Up-and-Go (TUG)), complex locomotion tasks (TUG, and walking with 90° turns), and a free everyday motor behavior (hand coordination task) which consisted of pouring water from a glass half-filled to an empty one on the opposite side of a table. For the locomotion tasks subjects were instructed to walk at their comfortable and natural speed. PD patients were known to have a highly variable gait pattern, reduced arm swing and arm swing asymmetry.

V. Feature Extraction

A. Low-level Features

Our goal here included the identification of differences between PD patients and healthy subjects movement patterns and the characterization and quantification of the various symptoms of the Parkinsons disease both of them based on motion data. The developed features, depicted in Fig. 2, cover common action phases such as walking and standing up, among others [7]. With these features, we were able to detect typical and already known abnormalities of PD patients such as shorter stride length, higher variance of step frequency, slightly further forward bent trunk during walking, slow and more unstable when standing up, a larger number of turning steps, slower arm movements during a precision arm movement. Moreover, we found abnormalities that are not known yet, such as different movement amplitudes and velocities during anterior-posterior and lateral hip and shoulder sway. The high number of movement abnormalities called for extracting more abstract features, as will be described in the next paragraph.

B. High-level Features

We started to develop several high-level features that we believe are clinically relevant for PD patients [8]. Subject

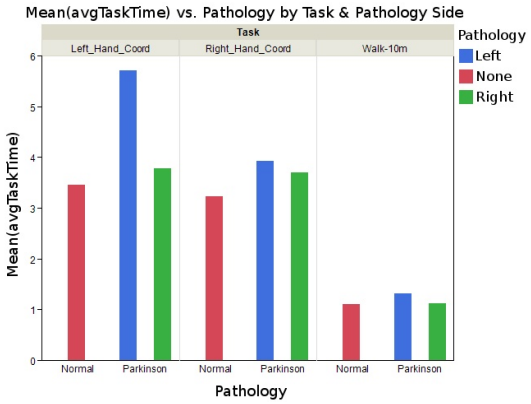

Fig. 3. Average task completion time. Mean values were calculated over many strides for 10m walk tasks [s/stride] and over 6 repetitions per side [s/repetition] in the case of the hand coordination task for both healthy and patient data.

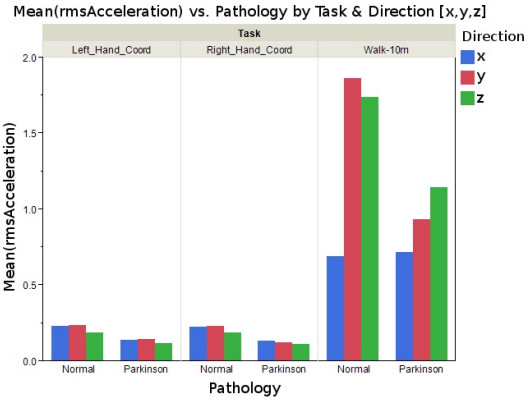

Fig. 4. Average linear acceleration RMS. Mean values of the rootmean-square of the acceleration traces of the average gait cycle (10m walk) and of the average hand motion (hand coordination task) for both healthy and patient data.

to our first investigation was the variability and smoothness of foot and hand movements during different tasks as well as the the correlation between these two movements classes. Variability was quantified by the root mean square (RMS) of movement trajectories which included linear velocity, acceleration, and jerk. Smoothness was studied in terms of acceleration and jerk measures. Preliminary results show that PD patients are slower than normal subjects in both hand coordination and walking (see Fig. 3), which is in agreement with previous studies. PD patients walked like they *cruised* around at a constant speed and with very little deviation around that cruising motion. This can be seen also in the average RMS of the acceleration data that is much lower in the PD than in the healthy group for the 10m walking and hand coordination task (see Fig. 4). However, this is not true in all directions, and our observations are in agreement with the concept of increased noise level in PD patients that explain some of their peculiar movement characteristics [5].

VI. Conclusions

First steps have been taken within this project to develop a closed-loop neural stimulation parameter calibration system

by extracting different levels of motion features across a variety of tasks in order to distinguish PD patients from healthy subjects. Our preliminary results have shown that motion abnormalities already known in PD patients can be detected from the data using a set of low-level features. Moreover, we started investigating unknown abnormalities by elaborating on high-level motion features. In the next steps of this project we intend to further extend the set of meaninigful motion features and to create a mapping between those features and the clinical state of a patient. Afterwards, we will face the challeging problem of mapping the state estimate into an adequate DBS stimulation parameter update.

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