Doctoral Dissertation Summary

Doctoral Program in Computer and Control Engineering (37th Cycle)

Vision-based, AI-powered approaches to motor functions characterization and rehabilitation

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Abstract

Human motion is a reservoir of health information, especially for the elderly and for individuals with neurodegenerative disorders such as Parkinson's disease. Alterations in motor functions, including difficulties in initiating motion, fine motor control, and coordination, may help predict the onset and progression of neurodegeneration without invasive examinations.

Despite the central role of motor functions in health assessment, accurately and reliably quantifying motor impairment is challenging. Motor symptom assessment for Parkinson's disease, for instance, still relies on the qualitative scoring assigned by clinicians, according to standardized scales such as the Unified Parkinson's Disease Rating Scale (UPDRS). Various sensors, including inertial measurement units, electromyographic sensors, and vision-based approaches, have been proposed to convert this qualitative evaluation into a quantitative assessment. The latter is especially relevant, as motion capture systems, relying on several calibrated and synchronized cameras, represent the gold standard for human movement analysis. However, motion capture systems are bulky, expensive, and require controlled environments such as indoor laboratories. As healthcare shifts towards telemedicine, new solutions are needed.

The advent of Artificial Intelligence (AI) is paving the way for new approaches to low-cost and portable video-based motion assessment. Deep Learning enables Human Pose Estimation (HPE) using multimodal data such as RGB-Depth video recordings or even simpler single-modality data, such as RGB videos recorded by a single smartphone or webcam. These HPE models generate a skeletal reconstruction of the human body across the frames of a video, similar to what can be achieved using complex motion capture systems. From these skeletal reconstructions, features can be derived to automatically estimate motion quality. However, as these methods are still novel, the validity of the extracted measurements and the derived motion parameters, as well as their ability to predict impairment in pathological subjects require thorough investigation.

In addition, video-based HPE allows for innovative human-computer interaction means, which may be exploited to implement exergames –i.e., gamed-based interventions for training and rehabilitation of motor functions. For conditions such as Parkinson's disease, motor training and rehabilitation are crucial for improving quality of life and counteract disease progression, as the neurodegeneration cannot be reversed.

This thesis aimed to contribute to this domain by conducting several experiments, with a special interest in applications for Parkinson's disease assessment and rehabilitation. These experiments focused on: validating the measurements provided by deep learning models for HPE during clinical assessment tasks, such as walking and hand dexterity exercises; optimizing learning models for recognizing Parkinson's disease symptoms; evaluating and predicting the effects of treatments like Deep Brain Stimulation; investigate the feasibility of integrating assessment and exergame-based rehabilitation, by introducing gamified versions of traditional assessment tasks.

The results achieved indicate that these new video-based, AI-powered approaches can capture relevant whole-body or hand-related motion profiles to characterize Parkinson's disease. However, methods that combine RGB and depth sensors may still provide more accurate and reliable results than purely RGB-based approaches.

Regarding automatic estimation of Parkinson's disease progression, the scientific literature and the experiments conducted suggest that pipelines trained using features obtained by video-based HPE can indeed recognize alterations peculiar to the disease. However, the limited training data available to the scientific community restricts the generalizability of these AI-based pipelines for automatic estimation of impairment. This requires introducing in this context new paradigms like semi-supervised learning, to obtain more robust solutions by exploiting also data lacking clinical supervision.

In the realm of exergaming, video-based HPE appears to be a feasible and effective tool for developing exergames that can support the training of motor functions, as well as the collection of assessment data that could be used by clinicians to improve patient follow-up.

This thesis demonstrates the feasibility of HPE models in enhancing video-based approaches to characterize and support Parkinson’s disease management, from different perspectives. However, further developments and in-depth studies are necessary. Future work will focus on expanding these pilot studies into larger experiments, potentially creating large-scale datasets and intelligent models using low-cost RGB cameras. Alternative techniques to traditional supervised learning will also be explored to address the shortage of labeled data, reducing the need for extensive clinical supervision. Finally, the physiological profiles of subjects during exergaming will be further investigated to develop real-time adaptive solutions that better meet the needs of pathological subjects.

Additional Information

This Dissertation illustrates the research activities conducted within the PhD Programme in Computer and Control Engineering, at Politecnico di Torino (Italy), and included several scientific contributions, published both in peer-reviewed international conferences and scientific journals.
The Programme had a total duration of 3 years (1st November 2021—31st October 2024).

All experimental activities envisaged a multidisciplinary approach and were conducted in cooperation with domain specialists in hospitals both in Italy and abroad.

In addition, a part of the research work was conducted at the Laboratory for Movement Biomechanics of ETH Zurich, during a secondment in the period November 2023—March 2024, and continued remotely until the end of the PhD.

I hereby declare that the contents and structure of this dissertation constitute my own original work and do not compromise in any way the rights of third parties, including those relating to the security of personal data.

Turin, 28th April 2025
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