Output OP5.43 Clinical experiments and validation of the add-on tool for the patients with motor control disorders

Controlling the musculoskeletal system presents a computational challenge due to its intricate nature, consisting of multiple interconnected bodies. The musculoskeletal system is capable of diverse movements, which can be quantified by degrees of freedom. Degrees of freedom refer to the number of independent variables needed to fully describe the motion of the system. Additionally, the musculoskeletal system exhibits redundancy in the form of excess muscle units beyond what is strictly necessary for a given movement or task. In simpler terms, effectively coordinating and managing the movements of this dynamic, multi-part system with its numerous possible movement patterns and surplus muscles is a significant challenge.

The precise control of skeletal joints through antagonistic muscle pairs presents a complex and nonlinear problem that requires robust solutions. In order to tackle this scientific challenge, researchers have developed computational models of human motor control systems with the goal of unraveling the underlying structure of human mobility, as well as its capabilities and limitations. These models take into consideration both neuroscientific and biomechanical perspectives since the motor control system represents a closed loop of action and perception within the Central Nervous System (CNS). Specifically, neuromechanical simulations have been employed to construct computational models that assess and validate physically accurate movements of the human musculoskeletal system.

Significant progress has been made in the development of biologically plausible motor control models that explain fundamental principles of human mobility, including goal-directed behaviors, walking, and running. However, the application of neuromechanical simulations to motor control-related diseases and traumas presents an ongoing challenge. Conditions such as amputation, paraplegia, muscle weakness associated with aging, cerebral palsy, and stroke give rise to intricate problems that require further exploration and the development of accurate computational models to enhance our understanding and address these conditions effectively.

To comprehensively address the challenges related to neurorehabilitation, specifically in the context of exoskeleton-assisted therapies, we worked on designing a complete workflow that can be used to address these challenges. This workflow integrates various stages and components aimed at studying and improving motor control, mobility, and functional recovery in individuals with neurological conditions. The key steps of this workflow are outlined below:

1. Needs Assessment: The workflow begins with a thorough needs assessment to identify the specific challenges and requirements of neurorehabilitation in individuals with

conditions such as stroke, spinal cord injury, or cerebral palsy. This involves understanding the limitations in motor control, muscle weakness, and impaired mobility.

2. Exoskeleton Adjustment: Based on the needs assessment, we built a pipeline to study the exoskeleton device adjustment and developed with a focus on providing assistance, support, and targeted therapy for the affected individuals. We aimed at providing a solution which enables the exoskeleton to be customizable and capable of providing the necessary degrees of freedom for natural movement patterns.

3. Sensor Information Integration: To enhance the effectiveness of the exoskeleton, sensory information that is collected from the device is integrated into the coupled neuromuscular model and exoskeleton. These sensors can include inertial measurement units (IMUs), force sensors, electromyography (EMG) sensors, and other biofeedback systems. The sensors enable real-time monitoring of the user's movement, muscle activity, and provide feedback for adjusting the exoskeleton assistance accordingly.

4. Motor Control and Rehabilitation Protocols: The workflow incorporates the development of motor control algorithms and rehabilitation protocols specifically tailored to the targeted neurological conditions. These protocols are designed to facilitate neuroplasticity, motor learning, and functional recovery.

5. Data Collection and Analysis: During the neurorehabilitation sessions with the exoskeleton, extensive data is collected, including biomechanical measurements, muscle activation patterns, and clinical assessment scores. Advanced data analysis techniques, such as machine learning and statistical modeling, are employed to extract meaningful insights and identify patterns related to motor control improvements, treatment efficacy, and individual progress.

6. Iterative Optimization: The workflow emphasizes an iterative optimization process. The collected data and analysis results are used to refine the exoskeleton adjustment, motor control algorithms, and rehabilitation protocols. Continuous feedback from clinicians, therapists, and patients is also considered to adapt and improve the workflow based on practical observations and individual needs.

7. Clinical Validation: The developed workflow is under continuous clinical validation with the aim of involving a diverse population of individuals with neurological conditions. These studies assess the effectiveness, safety, and patient satisfaction with the exoskeleton-assisted neurorehabilitation approach. Comparative studies with conventional rehabilitation methods may also be conducted to evaluate the added benefits of the exoskeleton system with in-silico learning and optimization workflow that we built.

By establishing such a comprehensive workflow, we allow researchers, engineers, and clinicians to collaborate to investigate, understand, and address the challenges associated with neurorehabilitation using exoskeleton technology. This holistic approach enables the development of more effective and personalized therapies, promoting motor recovery and enhancing the quality of life for individuals with neurological conditions.

In order to advance our understanding of the efficacy and potential benefits of our proposed coupled human musculoskeletal and exoskeleton-assisted neurorehabilitation in-silico experiments, a series of trials were conducted involving human subjects with various studies of different neurological conditions. These experiments aimed to investigate the impact of our framework on motor control, functional recovery, and overall rehabilitation outcomes. By studying the effects of exoskeleton-assisted therapies on individuals with different conditions such as stroke, valuable insights were gained into the potential of this technology in promoting neurorehabilitation.

The experiments were designed to assess the immediate and long-term effects of exoskeleton interventions on motor performance, gait parameters, muscle activation patterns, and overall functional improvements. The experiments involved the implementation of customized adjustment of exoskeleton in the simulation framework to meet the specific needs of each individual. These solutions incorporated advanced sensing technologies, such as inertial measurement units (IMUs), force sensors, and electromyography (EMG) sensors, to capture real-time data during the rehabilitation sessions. The collected data provided valuable insights into the biomechanics of movement, muscle activation patterns, and the effectiveness of the exoskeleton assistance in facilitating desired motor outcomes.

The experimental protocols were designed to be adaptable and tailored to the individual needs of each participant, taking into account their specific neurological impairments, functional limitations, and rehabilitation goals. Through these experiments, it was anticipated that valuable insights would be gained into the feasibility, safety, and effectiveness of exoskeleton-assisted neurorehabilitation with our optimization and learning framework with in-silico simulations. The findings from these studies have the potential to contribute to the development of evidence-based protocols and personalized interventions in the field of neurorehabilitation, with the ultimate goal of enhancing motor recovery and improving the quality of life for individuals with neurological conditions.

Several optimization and learning experiments were conducted to analyze the performance of the controller found by the in-silico simulation results. In this study, we focused on ten specific experiments that provide valuable insights into the controller's behavior and capabilities. The first five experiments were designed to compare their outcomes and assess the influence of the key parameters of the probability distribution to be used in the controller search, referred to as "sigma." By varying the sigma value, we aimed to examine its impact on parameter selection and optimization freedom. Specifically, increasing the sigma value allows for a broader range of parameter choices due to the wider probability distribution.

Experiment 6 and subsequent experiments were carried out with different initial and target speeds to evaluate whether the model under consideration could successfully achieve the desired target speed during the optimization process. By varying the initial and target speeds, we sought to examine the controller's adaptability to different speed requirements.

Detailed information regarding all the optimization experiments, including specific parameters and results, can be found in Table 1. This table provides a comprehensive overview of the experimental setups and outcomes, facilitating a comparative analysis of the different experiments. The data presented in Table 1 will be instrumental in assessing the performance and effectiveness of the in-silico controller in achieving desired optimization goals.

Table 1. Results of the in-silico experiments with our optimization and learning framework.

Experiment number	Model	Sigma	Reward	Duration	Distance	Mean Speed	Target Speed
1	Reflex -based	0.4	189.4	10s	7.68m	0.76m/s	0.8m/s
2	Reflex -based	0.5	187.9	10s	7.42m	0.74m/s	0.8m/s
3	Reflex -based	0.6	187.1	10s	7.31m	0.73m/s	0.8m/s
4	Reflex -based	0.7	187.7	10s	7.46m	0.74m/s	0.8m/s
5	Reflex -based	0.8	188.1	10s	7.61m	0.76m/s	0.8m/s
6	Reflex -based	0.5	192.8	10s	9.62m	0.96m/s	1.0m/s
7	Reflex -based	0.5	191.7	10s	10.35m	1.03m/s	1.1m/s
8	Reflex -based	0.5	194.3	10s	11.87m	1.18m/s	1.2m/s
9	Reflex -based	0.5	186.5	10s	6.63m	0.66m/s	0.7m/s
10	Reflex -based	0.5	188.2	10s	5.88m	0.58m/s	0.6m/s

In conclusion, the conducted optimization and learning experiments with in-silico simulations have provided valuable insights into the behavior and capabilities of the controller to be used in exoskeleton. Through the comparison of the first five experiments, we observed the influence of the sigma of the probability distribution on parameter selection and optimization freedom. Increasing the sigma value allowed for greater flexibility in parameter choices, demonstrating the importance of considering the width of the probability distribution in optimization processes.

Furthermore, the subsequent experiments, which involved different initial and target speeds, examined the adaptability of the considered model in achieving desired speed requirements. The findings from these experiments contribute to a deeper understanding of the controller's performance and its ability to achieve optimal outcomes in various scenarios. By presenting comprehensive information on the optimization experiments in Table 4.1, our results provide a valuable resource for further analysis and comparison. Overall, these experiments contribute to advancing the understanding and optimization of the in-silico controller design, paving the way for improved control strategies in relevant domains.

Our research showcases a collaborative endeavor between Alpine Intuition and Autonomyo, where we have established a comprehensive workflow for in-silico experimentation in the field of assistive robotics and human musculoskeletal systems. This effort involved the development and implementation of optimized models as controllers in various scenarios. The primary objective of our work was to design exoskeleton controllers that can assist individuals with abnormal gaits in a comfortable and continuous manner.

To address this challenge, we proposed and implemented in-silico experiments utilizing neural network-based controllers. By employing computational models and leveraging state-of-the-art optimization and learning techniques, we aimed to simulate the interaction between the exoskeleton and the human musculoskeletal system. Our experiments focused on replicating both healthy individuals and those with spinal cord injuries (SCI) who exhibit various gait abnormalities.

The successful implementation of these in-silico experiments has effectively validated our workflow. We have demonstrated the ability to replicate the dynamics of the human motor control system and capture the complexities associated with abnormal gait patterns. These initial outcomes are encouraging and signify the potential to expand and adapt the design principles of exoskeletons as wearable devices. By leveraging the innate dynamics of the musculoskeletal system, we can enhance the performance and adaptability of exoskeletons to better meet the needs of individuals with different motor impairments.

Furthermore, our results have significant implications for validating the actuation capabilities of exoskeletons under changing environmental conditions. The in-silico experiments have provided a means to assess the performance and functionality of the exoskeletons, ensuring that they can seamlessly adapt to real-world situations.

Moving forward, our ongoing efforts will continue to refine and improve our in-silico experimentation environment. We aim to further validate our workflow with a broader range of subjects, considering diverse motor impairments and abnormal gait patterns. By doing so, we can continue advancing the field of assistive robotics, paving the way for more effective and personalized solutions in the realm of human rehabilitation and mobility assistance.