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Highlight

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Hybrid Modalities Based Control of Assistive Ankle Foot Orthosis Robots for Stroke Rehabilitation

Abstract

In this three-year project, we developed a hybrid modalities-based control of assistive ankle-foot orthosis (AFO) robot for gait rehabilitation and evaluated its therapeutic effects through randomized controlled trial (RCT) in stroke survivors. In the first year of the project, the ankle-foot orthosis robot was designed and tested on the stroke survivors in Hong Kong, China. In the second year of the project, the ankle-foot orthosis was delivered to the Air University, and conducted the experiment and collected data from 20 healthy participants using fNIRS.

Aiming to promote collaboration, the First International Symposium on Robotics in Neuro-rehabilitation was held at Chinese University of Hong Kong in February, 2023; in the third year of the study, a team from mainland and HK, China visited Pakistan and attended the symposium on Robotics in Neuro-rehabilitation conducted at the Air University in Islamabad; the International Symposium on Stroke Rehab and Robotic Devices were organized by the Institute of Automation, Chinese Academy of Sciences in Beijing on May 8-9, 2025; the symposium was attended by the collaborating partners of the project and ANSO team members, which brought together collaborators and experts to discuss the latest advancements and enhanced closer collaborations.

Introduction

Stroke is caused by intracranial hemorrhage or thrombosis, which cuts off arterial supply to brain tissue and usually damages the motor pathway of the central nervous system (CNS) affecting one side of the body. Reduced descending neural drive to the paretic limb leads to hemiplegic gait in stroke patients. Worldwide there are more than 15 million people had stroke, mostly in countries with ageing population. About half of the stroke survivors lost their walking capacity immediately after stroke and only around 40% of them could regain gait independency after rehabilitation, with certain degree of muscle weakness and spasticity.

Researches in post-stroke hemiplegic gait pattern showed that stroke survivors walked with simplified modules based on electromyography (EMG) signals from leg muscles compared with healthy controls. In addition to the modification in modular organization, some abnormal muscle synergies and spastic synergistic activation patterns could also be observed in the affected leg. These asymmetric gait patterns reflected how the CNS responds to muscle weakness and poor motor control, to improve body support and locomotion. An important example is the foot drop gait abnormality commonly observed in stroke survivors, with the stiffen plantarflexed foot dragging on the ground during walking, which caused higher falling risk due to poor foot clearance.

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Compiled by Invited Contributor Prof Raymond Tong, The Chinese University of Hong Kong, and Prof Zeng-Guang Hou, Institute of Automation, Chinese Academy of Sciences

Robot-assisted gait training has been introduced to stroke rehabilitation in an attempt to facilitate task-oriented walking exercises, which often involves body-weight-supported treadmill system, equipped with exoskeleton (like Lokomat), or foot plates as an end-effector guidance (like G-EO system). The main advantage of these passive, stationary systems is to increase training intensity while relieve the workload of therapists. Contrary, some recent development in mobile exoskeleton robots demonstrated robotic assistance that encourages active participation on gait training in various walking terrains (like stairs) could further enhance walking speed and alter gait pattern of stroke patients.

Our research team in the Chinese University of Hong Kong developed an exoskeleton ankle robot as a lightweight (0.5kg on ankle) and portable orthotic device designed for robot-assisted gait training of stroke patients with foot drop gait abnormality before the start of this project. This robot has already been evaluated on chronic stroke (n=19) and sub-acute stroke (n=47) in multi-center randomized controlled trials. Results showed the robot-assisted gait training could significantly improve gait independence, walking speed, and promote confidence of heel strike.

Animal experiments and clinical studies on neuroplasticity in the brain suggested that high-intensity and repetitive exercises could stimulate motor recovery in multiple ways, such as promoting compensation in surviving brain area, improving interhemispheric connections, increasing synaptic plasticity, and accelerating neuronal reorganization and regeneration. Functional magnetic resonance imaging (fMRI) revealed task-oriented training using upper-limb rehabilitation robotics could induce connectivity alterations in motor area of the brain. However, the neurophysiological processes underlying the lower-limb gait recovery due to robot-assisted gait training have yet to be investigated. It would be interesting to explore the changes in different physiological signals (such as EMG, EEG, and fNIRS), at different time points of the robot-assisted gait training (i.e. before, during, and after gait recovery).
With a better understanding on the brain signal of stroke patients during gait training and using advanced signal processing and feature extraction methods (such as ARMAX model, adaptive ICA, etc.), brain computer interface (BCI) could be developed to enable control of the lower-limb rehabilitation robot directly from the brain, which might be able to stimulate brain recovery of motor cortex using a top-down rehabilitation approach.

Objectives of the Project

The objectives were to establish collaborations and facilitate research exchanges among Hong Kong, China, and Pakistan to improve stroke rehabilitation using ankle-foot orthosis and BCI. The goal was to focus on ANSO's strategic plans to encourage the exchange of ideas, review advancements, and outline future strategies aimed at enhancing healthcare for stroke patients. The target was to involve the utilization of a hybrid-modalities-based ankle-foot orthosis robot for gait rehabilitation and preliminary experiments were to be conducted on healthy subjects using the ankle robotic system. By the end of three years, all these objectives were successfully achieved. Additionally, research collaboration possibilities with other countries such as New Zealand, Saudi Arabia, United Arab Emirates, and Serbia were also explored, which have already resulted in starting of pilot research projects with different groups in these countries.

Relevance to ANSO Strategic Plan

In our project, we focused on rehabilitation of stroke patients under the sustainable development goal 3 (SDG 3) of the United Nation, which is about Good Health and Well-being aiming to ensure healthy lives and promoting well-being for all ages. ANSO is committed to promoting UN SDGs through catalyzing and implementing concrete international cooperation initiatives in Science, Technology & Innovation and Capacity Building (STIC). We designed the project to promote ANSO strategic plan for supporting SDG 3 by promoting scientific cooperation in health among its member countries (Hong Kong, Mailand China, and Pakistan), by capacity building in medical sciences, by introducing innovation & technology in healthcare, and by generating collaborative response to public health crises of stroke.

We used an evidence-based approach to explore how robot-assisted gait training could be beneficial in stroke rehabilitation. With an increasing trend of high incidence rate of stroke worldwide because of ageing population, disability caused by stroke and the elderly population would become a heavy burden to the healthcare system and society. Rehabilitation robotics offers a feasible solution to relieve the pressure on therapists and caregivers, as well as to deliver better quality rehabilitation to stroke survivors. In addition, this project also helped in exchanges of ideas, promote cooperation between collaborative institutes, extending the medium and long-term regional, social and economic cooperation of collaborative research, potentially with more research outputs (e.g. publications, patents).

Completed Tasks and Activities

In this project, we developed a hybrid modalities-based control of assistive ankle-foot orthosis (AFO) robot for gait rehabilitation and evaluated its therapeutic effects through randomized controlled trial (RCT) in stroke survivors.

First, we performed the experiment on healthy subjects and then collected and processed the data from stroke survivors. Additionally, four successful international symposiums were organized (two in Hong Kong, one in Pakistan, and one in Mailand, China) to disseminate the results of the project and to establish new collaborations. As a result of these symposiums, collaborations with New Zealand, Saudi Arabia, United Arab Emirates, and Serbia has already started in the field of neurorehabilitation with robotics.

Sharing of hybrid-modalities AFO Robot for Gait Rehabilitation

Summary

A hybrid-modalities ankle-foot orthosis (AFO) robot for gait rehabilitation was transferred to our collaborator at Air University Pakistan and preliminary experiments on healthy subjects with fNIRS were conducted.

Experiment

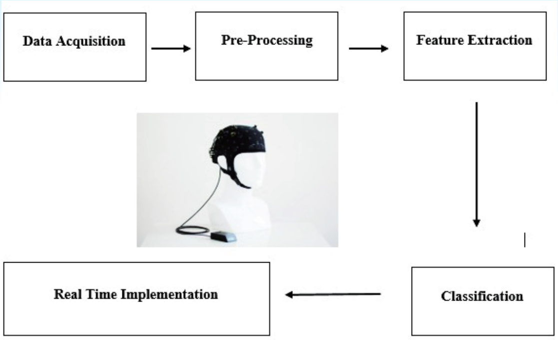
This research explored the feasibility of using an exoskeleton for ankle control assistance for stroke rehabilitation. The study involved the development of functional near-infrared spectroscopy (fNIRS)-based control system that could detect changes in the hemodynamic response of the brain associated with ankle movements. The system was tested on a group of healthy participants who performed ankle dorsiflexion and plantar flexion tasks while wearing an exoskeleton ankle joint. The fNIRS signals were then used to develop a learning model that predicted the desired ankle movement.

Experiment-Objectives

The objectives were the comparison of classification accuracies using classification algorithms for ankle dorsiflexion and planter flexion ankle movements, and the simulated online implementation of fNIRS-BCI control technique on prefabricated exo-ankle.

Experiment-Methodology

The schematic design of the robot-assisted gait training BCI-based system is as shown below. The figure shows the typical BCI system flow including data acquisition, pre-processing, feature extraction, and classification.



Schematic diagram of project methodology

Data acquisition setup with exoskeleton ankle robot

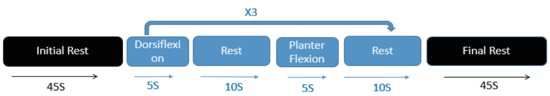
Experiment-Data Acquisition

We acquired neurophysiological signals using functional near-infrared spectroscopy (fNIRS) device NIRSport2 with sampling frequency of 10.1725Hz from 20 subjects (8 females) participants in good health with normal or corrected-to-normal vision. All individuals were right-handed and had an average age of 24±3 years. Following the literature, the primary motor cortex (M1) was recognized as the optimal region for collecting brain signals. Thus, we recorded the signals with 8x8 configuration from the left hemisphere's M1. None of the participants had a past record of motor impairment, visual problems, or neurological disorders.

For data collection, we modified the exoskeleton ankle robot from an articulated AFO with the ankle joint coupled with a rotatory servomotor and a torque amplifier that could provide powered assistance in ankle dorsiflexion and plantar flexion directions. The robot weighed 0.5 kg (including AFO and motor) on the leg, with the control box (0.5 kg) held by the trainer. Hence, this robot was lightweight and portable designed for robot-assisted gait training on both level walk and stair environments. The control algorithm of this exoskeleton ankle robot is extensible, which enabled research team to integrate the hybrid modalities brain computer interface control into the robot system.

Experiment-Paradigm

The experimental paradigm consisted of 150 seconds with 45 seconds of initial and final rest.

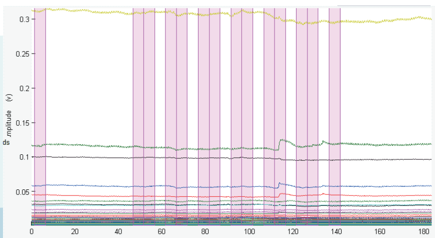


Experimental paradigm for data acquisition

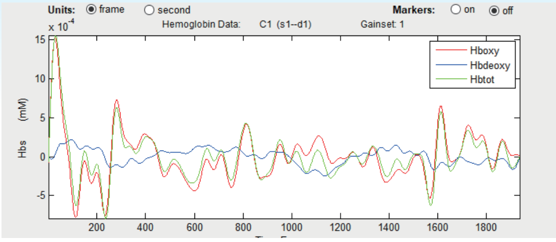
After the initial rest of 45 seconds the two motions (dorsiflexion and planter flexion) alternated for 5 seconds with the intermediate rest of 10 seconds. This loop was repeated 3 times, and the trial was completed with a 45 second rest at the end. The whole experiment was performed with the subjects wearing the exoskeleton ankle robot.

Experiment- Preprocessing

We processed the acquired neurophysiological signals and filtered them to remove different physiological, instrumental, and experimental noises. We used the Modified Beer-Lambert Law to convert raw optical density signals into oxy- and deoxy-haemoglobin concentration changes (ΔHbo and ΔHbR). To remove physiological or instrumental noises we filtered the signals using a Band-pass filter with a lower cut-off frequency of 0.01 Hz and a high cut-off frequency of 0.2 Hz.



Recording of raw fNIRS signals



Filtered data

Experiment- Feature Extraction

After pre-processing, the next step was to extract relevant features from the data. This involves identifying patterns or characteristics in the data that were related to the intended control task. We extracted different features including peak (P), mean (M), variance (V), skewness (S), and kurtosis (K) and their different combinations were used to find the best features combination for classification. The combination of mean, variance, skewness and kurtosis proved to be the best combination with highest accuracy for the classifiers.

Experiment-Classification

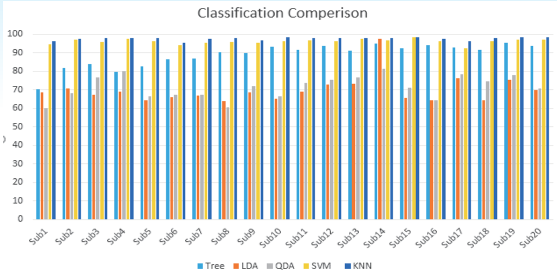
After the feature extraction, we trained five different classifiers and tested them. We trained and tested Decision Tree, Linear discriminate analysis (LDA), quadratic discriminant analysis (QDA), K-nearest neighbor (KNN) and Support vector machine (SVM) algorithms and KNN provided maximum accuracy out of them. The average accuracies were 88.94% for decision tree, 70.06% for LDA, 71.53% for QDA, 96.31% for SVM and 97.69% for KNN.

Outcomes

For classification, we tested a number of combinations of the features for all classifiers.

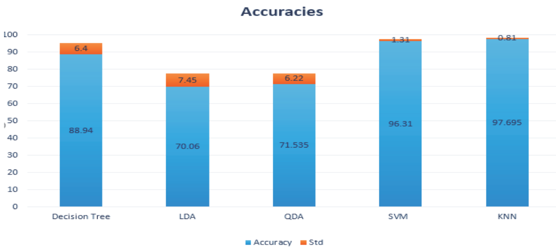
	MK	MP	MPV	Ms	MV	MVSk	SK	SP	VK	Vp	VS
DecisionTree	79.4	72.7	81.2	75.5	78.5	86.7	72.5	74.7	70.8	76.1	71.8
LDA	66.1	66.7	66.7	66.7	66.7	66.2	66.6	66.7	66.7	66.7	66.7
QDA	66	66.7	67.4	66.4	66.7	67.5	64.2	66.7	65.7	66.7	66.2
SVM	78.6	75.8	86.3	78.9	78.6	94.3	74.7	77.5	73.1	76.7	74.9
KNN	76.4	75.6	91.8	77.6	78.3	95.3	77.5	76.4	73.2	74.8	74

Classification of different combinations of the features



Classification Accuracies

The combination of mean, variance, skewness and kurtosis provided maximum accuracy for all the classifiers and in classifiers KNN performed the best. It is evident that on average KNN provided maximum accuracy (98.6%) while LDA provides the least accuracy of (64.4%).



Average classification accuracies

International Symposium on Robotics in Hong Kong, 2023

Summary

The symposium and poster session were organized at the Department of Biomedical Engineering, The Chinese University of Hong Kong in 2023.

Symposium

First International Symposium on Robotics in Neurorehabilitation (RNR-2023) was organized by Department of Biomedical Engineering, The Chinese University of Hong Kong (BME-CUHK) on February 16th, 2023. The symposium brought together collaborators and experts from China, Hong Kong, and Pakistan to discuss the latest advancements in the field of rehabilitation robotics, neurorehabilitation, and brain-computer interfaces. The symposium aimed to facilitate discussions among professionals and promote collaboration in this rapidly evolving field.

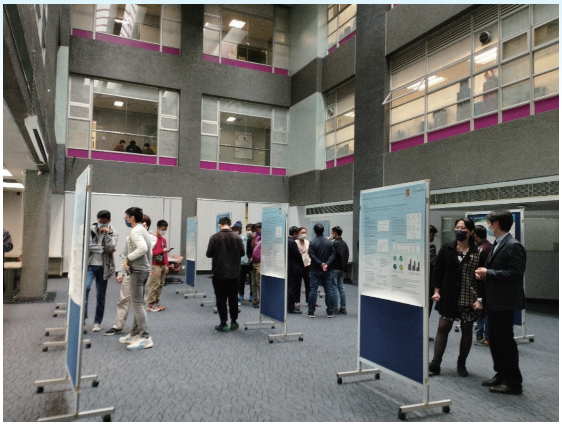
The symposium was chaired by Prof. Raymond Kai-Yu Tong from CUHK, with co-chairs Prof. Noman Naseer from Air University, Pakistan, Prof. Zeng-Guang Hou from the Chinese Academy of Sciences, and Prof. Rong Song from Sun Yat-Sen University, China. Together, they provided valuable insights into robotics in neurorehabilitation. The symposium covered a range of topics, including the use of robotics in stroke rehabilitation, the role of brain-computer interfaces in neurorehabilitation, and the development of assistive devices for individuals with disabilities.

Overall, the Symposium on Robotics in Neurorehabilitation provided an exciting opportunity for researchers, clinicians, and industry professionals to share their knowledge and expertise on the development of robotic aids for independent living for the elderly and disabled. The event was expected to inspire new ideas and foster collaborations that could benefit individuals with disabilities.

Group photo of the attendees

Poster Presentation

Keynote talks were followed by a poster session, where more than 30 posters were presented. The poster session facilitated the exchange of ideas and collaboration between researchers, which could lead to breakthroughs in the field and ultimately improve the lives of individuals with disabilities.



Poster promotion

Face to Face Meeting

A face-face meeting of all the collaborators was organized on 16th February 2023. Prof. Raymond Kai-Yu Tong from CUHK, Prof. Noman Naseer from Air University Pakistan, Prof. Zengguang Hou from Chinese Academy of Sciences, and Prof. Rong Song from Sun Yat-Sen University, China discussed the progress in year 2 and finalized a plan for year 3.

Face to face meeting

Near-to-Online BCI-System Testing

Summary
We wanted to test the BCI-system in real-time scenarios (online classification). However, due to the system limitation of data acquisition fNIRS system NIRSport2 this was not possible. Consequently, we decided to perform near-to-online system (simulated online) system.

Experiment

We recorded one complete trial of data and fed that trial data in real-time manner (without chunking, pre-processing and other steps), the concept was to test the system in near-to-real-time scenarios.

Experiment-Objectives

The objectives was the simulated online implementation of fNIRS-BCI control technique on prefabricated exo-ankle.

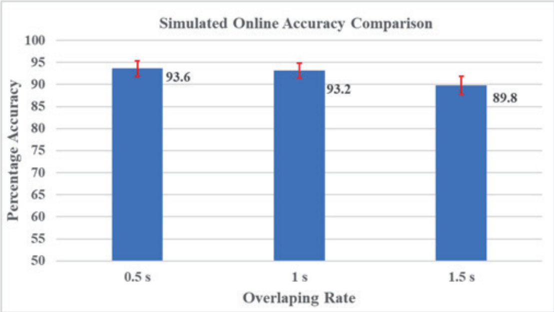
Experiment-Methodology

This technique was practically implemented on the test subject. The figure below shows the simulated online implementation of fNIRS signals for the ultra-short stump knee amputee. For simulated online implementation, a sliding or overlapping windowing technique is used with a window size of 25 points/ instances. The data was acquired from the left ankle and implemented on the right ankle for prosthetic control. This can also be implemented on the left ankle for rehabilitation purposes.

Simulated online implementation of fNIRS signals for the ultra-short stump knee amputee

Outcomes

After adjusting the rate of the overlapping window for durations of 5 points (which is nearly equivalent to 0.5 seconds) to 10 points (1 second) and then to 15 points (1.5 seconds), there was a noticeable decrease in accuracy. This decline strongly suggests that the optimal size of the overlapping step in the sliding or overlapping window technique is between 5 to 10 points (or 0.5-1 second).
The figure below provides a brief insight into simulated online accuracy results on the sliding rate of overlapping windows starting from 0.5 seconds to 1.5 seconds. It can be seen that on average the accuracy was better for smaller window sizes.



Simulated online accuracy results

International Symposium on Robotics in Pakistan, 2024

Summary

The symposium and poster session were organized at the Air University in Pakistan in 2024. Additionally, visits to stroke centers and universities in Pakistan were organized to explore possibilities of new collaborations.

Symposium

Second International Symposium on Robotics in Neurorehabilitation (RNR-2024) was hosted by Air University, Pakistan, in collaboration with the Alliance of International Science Organizations (ANSO), the Department of Biomedical Engineering at The Chinese University of Hong Kong (BME-CUHK), and the Chinese Academy of Sciences. The symposium brought together leading researchers, clinicians, and industry professionals from Pakistan, China, Hong Kong, and other countries to explore the latest advancements and emerging trends in rehabilitation robotics, neurorehabilitation, and brain-computer interfaces. Prof. Zeng-Guang Hou from the Chinese Academy of Sciences (CAS) was the Chief Guest along with Dr. Ahsan Khan and Prof. Sadia Shakil from The Chinese University of Hong Kong. The symposium was chaired by Prof. Noman Naseer from Air University, Pakistan. The aim was to foster international collaboration and exchange of knowledge in this rapidly developing field, ultimately driving progress towards improved rehabilitation outcomes for individuals with neurological disorders and disabilities.

Group photo of the attendees

Similar to the 2023 symposium, RNR-2024 featured keynote presentations by distinguished experts in the field, followed by an interactive poster session.

Overall, the RNR-2024 symposium served as a valuable platform for researchers, clinicians, and industry stakeholders to share their expertise and insights. The event is expected to inspire novel research directions and collaborations that will ultimately benefit individuals with disabilities by promoting the development of more effective and accessible rehabilitation technologies.

Poster Presentation

The poster session showcased cutting-edge research from a wide range of participants, facilitating discussions and potential collaborations that could lead to significant breakthroughs in the field. The symposium discussions spanned various topics, including the application of robotics in post-stroke rehabilitation, the potential of brain-computer interfaces in neurorehabilitation, and the development of advanced assistive technologies to improve the lives of people with disabilities.

Collaboration Visit

Visit to Riphah International University in Pakistan having the largest stroke rehabilitation facility in Pakistan was organized. As a result of this visit strong collaboration has already started with Riphah International Hospital in which we collected data of stroke survivors from their hospital for our project. The department of biomedical engineering at the Chinese University of Hong Kong has also started collaborations with the hospital on some other projects which involve stroke rehabilitation using augmented reality and soft robotic hand.

International Symposium on Robotics in Hong Kong, 2024

Summary

The symposium and poster session were organized by the department of Biomedical Engineering, Chinese University of Hong Kong on December 03-04, 2024. In addition to the project collaborators from Hong Kong, Mainland, and Pakistan, researchers, scientists, and clinicians, and industries from New Zealand, United Arab Emirates, Saudi Arabia, and Serbia delivered talks on their state-of-art research on stroke rehabilitation with robotics.

Symposium

The International Symposium on Robotics in Neurorehabilitation (RNR 2024) was successfully held on December 03-04, 2024, building upon the momentum of the inaugural symposium organized in Hong Kong in 2023 by Prof. Raymond Tong, CUHK and the symposium at Air University Pakistan during February 2024. This event was hosted by CUHK, Hong Kong, in collaboration with The Alliance of International Science Organizations (ANSO), and the Department of Biomedical Engineering at The Chinese University of Hong Kong (BME-CUHK). The symposium brought together leading researchers, clinicians, and industry professionals from Pakistan, Hong Kong, Mainland, Serbia, United Arab Emirates, Saudi Arabia, and New Zealand to explore the latest advancements and emerging trends in rehabilitation robotics, neurorehabilitation, and brain-computer interfaces. Professor Ho Pui Aaron Ho, the chairman of BME-CUHK was the chief guest of the symposium. The symposium was organized by Prof. Raymond Tong and Prof. Sadia Shakil from BME-CUHK. Prof. Tong chaired the symposium and was also one of the keynote speakers. The aim of the symposium was to foster international collaboration and exchange of knowledge in this rapidly developing field, ultimately driving progress towards improved rehabilitation outcomes for individuals with neurological disorders and disabilities.

Overall, the RNR 2024 symposium served as a valuable platform for researchers, clinicians, and industry stakeholders to share their expertise and insights. The event is expected to inspire novel research directions and collaborations that will ultimately benefit individuals with disabilities by promoting the development of more effective and accessible rehabilitation technologies.

Group photo of the attendees

Poster Presentation

A poster session was held after the talks in which students and researchers from collaborating countries of Hong Kong, Mainland, and Pakistan showcased their work on stroke rehabilitation. More than 30 posters were displayed in the poster session and were well received by a large number of visitors.

Poster promotion

Labs Visits

RNR 2024 also included distinguished guests' visits of various labs of BME-CUHK. The guests were inspired by the cutting-edge research and development done in various labs and by the latest technology used for these tasks. They showed keen interest and enthusiasm to immediately start active collaboration with BME-CUHK.

Experiment and Testing on Drop Foot Patients

Summary

The hybrid-modalities ankle-foot orthosis (AFO) robot for gait rehabilitation was used to collect data from drop foot patients from the Railway Hospital in Pakistan affiliated with Riphah International University.

Experiment

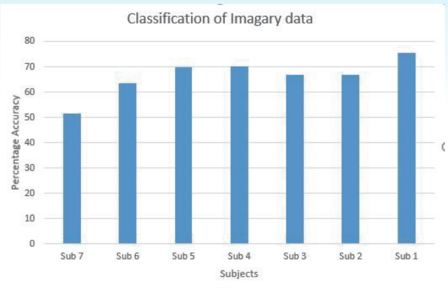
Data was acquired from 7 drop foot patients at Railway Hospital, Pakistan. The participants' age group was 61 ± 7 years, 5 were male and 2 female participants. Data was acquired wearing the ankle-foot robotic device and fNIRS. Data was recorded for two ankle movements, Dorsiflexion and Plantar flexion. Each movement was performed under two conditions, Motor execution and Motor imagery.

Experiment-Methodology

The experiment consisted of showing the video of foot movements to the patients followed by initial rest of 45 seconds. Afterwards, fNIRS data was recorded during Dorsiflexion and Plantar Flexion movements of the ankle assisted by ankle-foot robot. These movements were repeated three times with a separation of 15 seconds of rest in between any two movements.

Outcomes

Three machine learning classifiers were tested including LDA, QDA and SVM. Three class data sets were considered (Dorsiflexion, Planter, Rest). The results show average of 65.08 ± 3.5 percent accuracy for motor execution and 66.29 ± 8.1 percent on imagery data set using QDA.



Classification accuracies for imagery data

International Symposium on Stroke Rehab in Beijing, 2025

Summary

The international symposium and poster session were organized by the Institute of Automation, Chinese Academy of Sciences in Beijing on May 8-9, 2025. The symposium was attended by the collaborating partners of the project and ANSO team members.

Symposium

The International Symposium on Stroke Rehab and Robotic Devices was successfully held on May 08-09, 2025, in Beijing. The symposium was co-chaired by Prof. Zeng-Guang Hou from the CASIA and Prof. Sadia Shakil from CUHK. Welcome addresses were delivered by Prof. Sadia Shakil and Prof. Zhijun Yi from ANSO. Prof. Raymond Tong from CUHK was the keynote speaker at the symposium. Prof. Noman Naseer from the Air University in Pakistan and leading researchers, clinicians, and industry professionals from Mainland and Hong Kong delivered talks on their state-of-the-art research on rehabilitation robotics. The aim of the symposium was to share research on the use of robotics for stroke rehabilitation.


Group photo of the attendees

Poster Presentations

There was an interactive poster session during the symposium that showcased cutting-edge research from work done by various groups working on rehabilitation robotics.

Labs Visits

The symposium also included distinguished guests' visits of various labs of CASIA focused on robotics-based rehab. The guests were inspired by the cutting-edge research and development done in various labs and by the latest technology used for these tasks.

Hospital Visits

The team of researchers from CUHK and Air University in Pakistan visited the China Rehabilitation Research Center or the Boai Hospital. The visitors were warmly welcomed by the hospital and were shown various rehab centers including stroke rehab, music therapy, prosthetics, and Chinese medicine. The visitors also discussed various collaboration possibilities with the hospital.

Team Collaboration in Three Years

Responsibility and Activities of Principal Investigator

Prof. Raymond Tong has developed the Ankle robotic system and had published in top journal in the rehabilitation field, and the system has conducted clinical trial and showed functional improvement on stroke survivors. His research team has already funded by the Hong Kong Jockey Club Charities Trust to deliver the systems in 40 centers in stroke rehabilitation.

Prof. Tong supervised the transportation of the ankle robotic system to Pakistan and arranged for the training of the team in Pakistan. During the implementation of the project, Prof. Tong also supervised various activities such as constant communication with the collaborators, organizing symposia, and conducting regular online meetings to guide the collaborators.

Responsibility and Activities of Collaborators and Teams

Prof. Naseer is an expert in brain signals Functional near-infrared spectroscopy (fNIRS)-based brain-computer interfaces (BCIs), which can further enhance the robotic control by brain signals to develop the next generation of robotic system for stroke rehabilitation. His team was responsible for the data collection and its processing in Pakistan. One manuscript has been prepared from the work that will be submitted to a journal soon.

Prof. Rong Song has joint journal publications with Prof. Tong on EMG and robotic control. He was involved in assisting Prof. Naseer's team in conducting data analysis. Prof. Hou's research is in robotic control systems and further enhancement of the system performance. He was involved in suggesting the robotic system improvements that contributed towards the design of effective ankle-foot orthosis.

Difficulties and Risk Management

Potential Difficulties

1. Technical Limitations of fNIRS and Real-time BCI

- **Issue:** fNIRS has lower temporal resolution compared to EEG, and hardware like NIRSport2 used in the project could not support true real-time online classification.
- **Impact:** This limited the testing of live BCI applications and forced reliance on simulated online experiments.
- **Risk:** Could hinder clinical applicability or delay translational progress into real-time rehab setups.

2. Inter-Subject Variability in Brain Signals

- **Issue:** Significant variation in brain signal strength and patterns across individuals, especially in stroke patients with damaged neural networks.
- **Impact**: Lower classification accuracy in motor imagery/execution tasks for patients compared to healthy participants.
- **Risk:** May reduce reliability of BCI-controlled AFO in clinical settings.

3. Hardware Transport and Maintenance Challenges

- **Issue:** Shipping and operating delicate robotic hardware and fNIRS systems across international borders (e.g., from Hong Kong to Pakistan).
- **Impact:** Risk of damage, calibration drift, or lack of technical support at remote sites.
- **Risk:** Delays in experiments, compromised data quality, or added costs.

4. Stroke Patients' Lack of Awareness

- **Issue:** Stroke patients in Pakistan have always experience manual rehabilitation and the use of technology for this purpose was new to them.
- **Impact:** It was challenging to make the patients follow the instructions properly while data collection with fNIRS using ankle-foot orthosis.
- **Risk:** Not meeting experimental criteria, bad data quality, low classification accuracy.

5. Limited Real-world Testing and Generalizability

- **Issue:** Most data collection was done under controlled lab conditions or with small patient groups.
- **Impact:** Potential lack of generalizability of the system for broader patient populations or real-world use.
- **Risk:** Innovation may remain confined to academic settings unless commercial or clinical partners are engaged.

Risk Management Strategies

1. Simulated Online Testing and Modular Architecture

- **Mitigation:** Simulated near-real-time testing was implemented to validate the feasibility of BCI control flow.
- **Strategy:** Future versions can integrate faster acquisition systems (e.g., hybrid EEG + fNIRS) for better real-time response.

2. Robust Machine Learning Pipeline

- **Mitigation:** Multiple classifiers were tested and the most stable (KNN and SVM) were selected.
- **Strategy:** Further training with more stroke patient data, or adaptive algorithms (e.g., transfer learning) can improve generalizability.

3.Remote Technical Support and Lightweight Design

- **Mitigation:** The AFO robot was designed to be lightweight (0.5 kg) and modular, easing transport and setup.
- **Strategy:** Documentation, video tutorials, and spare parts kits can be sent to satellite sites to reduce downtime.

4. Pre-training of the Patients

- **Mitigation:** Patients were pre-trained about the use of equipment.
- **Strategy:** Patients were informed about the ankle-foot orthosis and fNIRS use a day before the experiment. However, the patients were still not comfortable with them, which is evident from low classification accuracies.

5.Symposiums to Catalyze Broader Collaborations

- **Mitigation:** Hosting annual international symposiums broadened exposure and brought in new institutional partners from UAE, Serbia, etc.
- **Strategy:** Expand to include industrial partners or health ministries to ease transition from research to implementation.

Achievements

Main Achievement 1

Development and Validation of a Hybrid-Modality AFO Control System Using Brain Signals:
One of the most significant achievements of the project was the successful development, implementation, and validation of a brain-controlled assistive ankle-foot orthosis (AFO) for stroke rehabilitation, integrating hybrid-modalities such as fNIRS and robotics.

The methodology included a comprehensive BCI pipeline: data acquisition, preprocessing, feature extraction (including statistical metrics like mean, variance, skewness, and kurtosis), and classification using five different algorithms (Decision Tree, LDA, QDA, KNN, and SVM). Results showed K-Nearest Neighbor (KNN) classifier achieved a peak accuracy of 97.69%, making it highly effective in decoding motor intentions from fNIRS signals.

Main Achievement 2

Establishment of a Multi-National Collaborative Platform in Neurorehabilitation Robotics:
The second major achievement was the creation of a vibrant international collaboration platform between Hong Kong, Mainland China, and Pakistan—and eventually extended to countries like New Zealand, Saudi Arabia, UAE, and Serbia—through a series of four high-impact international symposiums.

As a result of these symposia, a new ecosystem for robotic stroke rehabilitation emerged across continents. These events not only strengthened cooperation but also initiated long-term MoUs, co-authored papers, joint data collection, and shared lab access—key outcomes envisioned in ANSO's strategic goals.

This achievement exemplifies scientific diplomacy in action, using health technology as a tool to unite countries and accelerate innovation in stroke rehabilitation. It aligns strongly with SDG 3 (Health & Well-being) and ANSO's mission to catalyze international scientific cooperation for societal impact.