WARSAW UNIVERSITY OF TECHNOLOGY

DISCIPLINE OF SCIENCE: AUTOMATION, ELECTRONICS, ELECTRICAL
ENGINEERING AND SPACE TECHNOLOGIES
FIELD OF SCIENCE: ENGINEERING AND TECHNOLOGY

Ph.D. Thesis

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Possibilities and efficacy of including ICT technologies in robot-aided distant home rehabilitation

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Warsaw, 2024

Acknowledgment

The presented doctoral thesis was conducted in the years 2020-2024 within *Implementation Doctorate* programme organised by *Ministry of Science and Higher Education of the Republic of Poland.* All the works were held in cooperation between *Warsaw University of Technology* and *Łukasiewicz Research Network – Industrial Research Institute for Automation and Measurements PIAP.* The results of the research and development are being implemented in new products of the Institute - the devices for robot-aided rehabilitation. I want to thank all the people who supported me in my way, both emotionally and professionally - my family and close friends for their love and for always being there for me; supervisors for trust; colleagues from the Institute working on biorobotics for technical support and endless ideas; researchers, medical doctors, and physiotherapists who consulted me during my investigation for their invaluable insights; and my managers who believed in my vision and pushed me forward.

Title:
Possibilities and efficacy of including ICT technologies in robot-aided distant home rehabilitation

Abstract:

Due to the shortages in medical staff, including in the area of physiotherapy, patients do not receive the required service in a sufficient amount of time and quickly enough. When it comes to physical rehabilitation, such a situation can result in undesirable side effects, including not complete possible convalescence. Due to this, the patients remain less independent and require the support of others in daily living activities. The physiotherapy robots can provide kinesiotherapy to multiple patients, even in a home environment. Either end effector-type robotic arms or exoskeletons are applicable for this task. The former is easier to implement and meets safety criteria, but the latter enables monitoring and mobilising separate motions in joints individually. However, they both still require the supervision of physiotherapists. Nevertheless, their fleet can be placed in more available non-medical institutions, not located in large cities only, and used for minimally supervised semi-automatic exercises with the possibility of teleoperation. This requires the development of effective accompanying technologies to provide safety and automation of treatment. The study aims to examine the effects of exoskeleton-aided therapy on patients' musculoskeletal systems compared to conventional therapy based on the developed EMG-based assessment algorithms and the capabilities of using VR technology for visualising exercises.

The investigation includes analysing users' needs and limitations, simulating exercises, designing and prototyping a 3D-printed exoskeleton, developing an EMG-based assessment algorithm, creating a VR-based visualising environment for the system's user, and experiments with volunteers. The design process was conducted based on the design intent and corresponding standards for medical devices. The simulations included multibody dynamics analysis and mechanical strength analysis combined with optimisation using the finite element method. Experiments included kinematics measurements with various types of encoders and measuring the activity of muscles with EMG sensors.

The exoskeleton was prototyped using two 3D printing technologies. The fused filament technique was used for sliding components, while the powder technology was used for the main constructional bodies. It enables full mobility of shoulder and elbow joints while driving only three degrees of freedom. The internal/external rotations remained as free by implementing passive open bearings. The control system was integrated with VR phantom-based visualisation of exercises and the passive exoskeleton for registering motions. Moreover, a digital twin of the exoskeleton was developed to enable teleoperation and remote monitoring of treatment. The device was prepared for passive physiotherapy and enabled manual registering of motion and automatic following of the recorded trajectories.

The developed technologies were tested in two trials. The first one included repeating recorded motions with different types of visualisation - 2D sliders, 3D phantoms, and VR phantoms. The trials were conducted with a passive exoskeleton measuring the joint rotations. It was observed that no significant differences in achieved motion accuracy appear between the phantom-based visualisation presented on a flat screen and in a VR headset. Following, the trials with the active exoskeleton were organised. The electrical activity of the participant's muscular groups was compared for the simulated task-oriented sessions. The analysis proved that the muscular activations remain at a similar level, and the appropriate groups are activated for both the manual and exoskeleton-aided treatment.

The outcomes of the thesis prove that the exoskeletons can be used to perform kinesiotherapy as a real-life physiotherapist in terms of engaging a patient's muscular system. However, the initial prototype's bulkiness and lack of rigidity in initial parts limited some of the motions and excessively loaded shoulder joints. Moreover, the ICT solutions accompanying the robot-aided treatment exceed the capabilities of the robotic systems. Nevertheless, their effectiveness should be validated, as some of them do not improve a patient's performance.

Key words:

EMG, exoskeleton, home therapy, ICT, kinesiotherapy, task-oriented rehabilitation, telerehabilitation, rehabilitation robotics, VR

Tytuł:

Możliwości i efektywność włączenia technologii ICT do zdalnej zrobotyzowanej rehabilitacji domowej

Abstrakt:

W związku z brakami kadrowymi, w tym w obszarze fizjoterapii, pacjenci nie otrzymują potrzebnej im pomocy w odpowiedniej ilości i odpowiednio szybko. W przypadku rehabilitacji ruchowej taka sytuacja może skutkować niepożądanymi skutkami ubocznymi, w tym niepełnym potencjalnie możliwym powrotem do zdrowia. W takim przypadku pacjenci pozostają mniej samodzielni i wymagają intensywnego wsparcia innych osób w aktywnościach życia codziennego. Roboty do fizjoterapii mogą pomagać wielu takim osobom, również w warunkach domowych. Do tego zadania można zastosować wodzące ramiona robotyczne lub egzoszkielety. Pierwsze są łatwiejsza w wykonaniu i zazwyczaj są bezpieczniejsze w użytkowaniu, natomiast drugie umożliwiają obserwację i wspieranie osobno pojedynczych ruchów w stawach. Obydwa rozwiązania wymagają jednak nadal nadzoru fizjoterapeutów. Ich floty można jednak umieścić w bardziej dostępnych placówkach pozamedycznych, nie zlokalizowanych wyłącznie w dużych miastach, i wykorzystać do terapii półautomatycznej przy minimalnym, potencjalnie zdalnym, nadzorze. Wymaga to opracowania skutecznych technologii towarzyszących zapewniających bezpieczeństwo i automatyzację ćwiczeń. Celem niniejszej pracy jest zbadanie wpływu terapii wspomaganej egzoszkieletem na układ mięśniowo-szkieletowy pacjentów w porównaniu z terapią konwencjonalną w oparciu o opracowane algorytmy oceny oparte na EMG, oraz możliwości wykorzystania technologii VR do wizualizacji ćwiczeń pacjentowi.

Zrealizowane zadania objęły analizę potrzeb i ograniczeń użytkowników, symulację ćwiczeń, zaprojektowanie i prototypowanie egzoszkieletu drukowanego w 3D, opracowanie algorytmu oceny opartego na EMG, stworzenie środowiska wizualizacji dla użytkownika systemu opartego na VR oraz eksperymenty z ochotnikami. Proces projektowania przeprowadzono w oparciu o założenia projektowe i odpowiednie normy dotyczące wyrobów medycznych. Symulacje zawierały analizę dynamiki metodą wieloczłonową oraz analizę wytrzymałości mechaniki i optymalizację metodą elementów skończonych. Eksperymenty wykorzystywały pomiary kinematyki za pomocą różnego rodzaju enkoderów oraz pomiar aktywności mięśni za pomocą czujników EMG.

Prototyp egzoszkieletu został wytworzony przy użyciu dwóch technologii druku 3D. Do elementów ślizgowych zastosowano przetapianie filamentów, natomiast w głównych elementach nośnych - technologię proszkową. System umożliwia pełną mobilność stawów barkowego i łokciowego, natomiast napędza wyłacznie trzy stopnie swobody. Rotacje wewnętrzne / zewnętrzne pozostały wolne dzięki zastosowaniu pasywnych łożysk otwartych. System sterowania został zintegrowany z wizualizacją ćwiczeń opartą na modelach człowieka w VR oraz pasywnym egzoszkieletem rejestrującym ruchy. Ponadto opracowany został cyfrowy bliźniak egzoszkieletu, który umożliwia teleoperację i zdalne monitorowanie terapii. Urządzenie zostało przygotowane do fizjoterapii biernej i umożliwiało manualną rejestrację ruchu oraz automatyczne powtarzanie zarejestrowanych trajektorii.

Opracowane technologie zostały przetestowane w dwóch próbach. Pierwsza polegała na powtarzaniu zarejestrowanych ruchów z różnymi rodzajami wizualizacji – wskaźnikami suwakowymi w 2D, modelami użytkownika w 3D i modelami użytkownika w VR. Badania przeprowadzono z pasywnym egzoszkieletem mierzącym obroty w stawach. Zaobserwowano, że pomiędzy wizualizacjami z modelami człowieka prezentowanymi na płaskim ekranie a w goglach VR nie występują istotne różnice w zakresie dokładności wykonywania ćwiczeń.

Następnie przeprowadzone zostały próby z egzoszkieletem aktywnym. Porównano aktywność elektryczną grup mięśni uczestników podczas symulowanych sesji funkcjonalnych. Analiza wykazała, że aktywacje mięśni są na podobnym poziomie, a odpowiednie grupy aktywują się poprawnie, zarówno w przypadku terapii manualnej, jak i wspomaganej egzoszkieletem.

Wyniki pracy dowodzą, że egzoszkielety mogą być skutecznie wykorzystywane w kinezyterapii, umożliwiając ćwiczenie jak z prawdziwym fizjoterapeutą w zakresie angażowania układu mięśniowego pacjenta. Dość duże rozmiary prototypu i brak wystarczającej sztywności jego pierwszych członów nośnych ograniczały jednak niektóre ruchy i nadmiernie obciążały okolice stawu barkowego. Co więcej, wdrażanie rozwiązań ICT do terapii zrobotyzowanej pozwala rozszerzyć jej możliwości. Skuteczność konkretnie wybranych technologii powinna być jednak weryfikowana, ponieważ niektóre z nich, mimo pozornej skuteczności, nie poprawiają osiągów pacjenta.

Słowa kluczowe:

EMG, egzoszkielet, ICT, kinezyterapia, rehabilitacja funkcjonalna, robotyka rehabilitacyjna, telerehabilitacja, terapia domowa, VR

Contents

1 State of the Art

1.1 Introduction

The doctoral thesis is dedicated to the remote home physical rehabilitation of extremities, the upper in particular. Investigation and development works are focused in general on robot-aided kinesiotherapy rather than a particular medical case. For this reason, the background of neurological, orthopaedic, post-trauma and post-surgical patients is considered. This section contains the presentation of relevant contemporary methods of physical rehabilitation, recommendations for such therapy, analysis of recovery processes for selected cases, insights into robot-aided therapy, an overview of information and communication technologies (ICTs) already used for rehabilitation, and the discussion on remote home treatment. These are used in the further part of the work to design the system filling the market niche and scientific gap regarding the topic.

1.2 Methods of physiotherapy

Physiotherapy (or physical therapy) is a complex process of restoring the maximum possible functionality lost by a patient. It is realised by the professionals through examination, evaluation, diagnosis, prognosis and finally - physical intervention [111]. The analysed physiotherapy is limited mostly to motor and orthopaedic cases. For such, basic treatment consists of passive and active techniques. The first type is dedicated mainly to the ones who lack basic motor skills enabling motion. Mobilisation of body segments or massages performed by a professional can be used to prevent stiffness in joints and stretch muscles. On the contrary, active rehabilitation is beneficial for the ones with basic motor capabilities, as it helps them retrain neurological connections and regain the ability to move [83][79].

In general, physiotherapy is a part of medical rehabilitation. It consists of various techniques such as medical massage, physiotherapy with physical triggers (e.g. functional electrical stimulation [110]), and kinesiotherapy - the treatment by motion [83][111].

The last mentioned is one of the most popular methods used by physiotherapists. It may be realised with either support or resistance, depending on the patient's needs. The approach to motor rehabilitation strictly depends on the patient's condition and the cause of their impairment [79]. For neurological diseases, physical treatment is not only recovering the physical performance of the musculoskeletal system but also redeveloping cognitive associations of neurological triggers with activities. For such cases, the general aerobic exercises are favourable to be combined with task-specific training [45]. Contemporary studies investigate the effects of mobilising multiple joints while realising daily life motion patterns. These can contribute to faster recalling neurological system connections and increasing motivation of the patient[93][17]. For these reasons, function-oriented physiotherapy is one of the leading trends in kinesiotherapy.

Additionally to the mentioned, nowadays, professionals combine physical rehabilitation with innovative tools. These can contribute to better diagnostics, faster recovery and more efficient therapy. As to combining treatment by motion with the therapy by physical triggers, the use of electrical or magnetic stimulation is typical [110]. Also, implementation of ICTs and gamification of therapy gains in popularity [59][139][34][86]. This helps in enhancing patient's engagement; thus, motivating them to keep exercising regularly. Moreover, new approaches to cognitive-motor therapy have been developed. Examples of such are mirror therapy [135][93], or error augmentation [90].

As for most fields of science, physiotherapy is an ongoing automation and robotisation process. A blend of these fields of medicine and engineering brought rehabilitation robotics to life. Today, there are numerous commercially available devices supporting physiotherapists in their work - both for passive and active therapy [120]. Furthermore, interest in developing new systems and introducing them to clinical practice is rising [22].

1.3 Physiotherapy process

Physiotherapy is the process of recovering the maximum available physical performance of a patient with a certain level of impairment. Patients with lighter motion disorders can benefit from exercising by recalling their motion capabilities and connecting them with genuine neurological patterns. On the contrary, patients with severe disabilities require mobilising their joints to prevent them from stiffness [111].

The process of physiotherapy typically begins with the history interview, examination of patients' conditions and assigning them appropriate methods and rehabilitation intensity [111]. This should include analysing medical history, indicating areas of pain, measuring active/passive ranges of motion and strength, as well as functional tests or other tests corresponding to the particular case [111]. At this stage, the specialist decides on the form of the therapy - physical agents, manual methods or therapeutic exercises [111]. Following, the leading physiotherapist sets the goals that either standard measurable parameters or the goals [97][130]. Such an approach remains in line with the concept of human-centred medicine. After qualifying the patient and setting the aim of the treatment, the intervention begins. The sessions of activities are planned and realised in specialist institutions or home environments - mainly for patients with severe diseases. Many exercises can be realised with the use of additional devices. The therapy is monitored by the physiotherapist, and the session routine is designed based on their observations or measurements. The effects of treatment are assessed according to the targets planned, with functional tests and biomechanical measures. These include balance, aerobic capacity, range of motion, motor functions, pain, posture, and self-care domestic life, among others [111]. The outcomes of the therapy are assessed upon discharge but may also be monitored at the follow-up.

In general, the routine of physiotherapy follows the general scheme [111]:

- History interview
- Examination with tests and measurements
- Evaluation and the diagnosis with prognosis and expected range of visits
- Goals setting
- Designing the plan of care
- Intervention (physiotherapy sessions with examinations)
- Final examination and discharge

As mentioned before, the intensity and method of mobilisation should be adjusted to the patient's health conditions. The main criteria for selecting the appropriate approach to the therapy should be the results of the initial examination [111]. However, for the severe cases, additional means should be deeply analysed - respiratory and cardiovascular reserves, as well as physical appearance, blood parameters, and temperature [68]. Moreover, the history of traumas and surgeries have to be considered while designing the therapy routine [14].

1.3.1 Post-stroke recovery process

According to World Health Organisation (WHO), stroke is „rapidly developed clinical signs of focal (or global) disturbance of cerebral function, lasting more than 24 hours or leading to death, with no apparent cause other than of vascular origin" [38]. It is the most common cause of people's disabilities in developed countries [131][138][142][116]. Yearly, almost 800,000 people suffer from stroke and 60% of them require rehabilitation [87]. Statistically, six months after the cerebrovascular accident, 30% of patients require help in their daily activities, and 26% of them are fully dependent on other persons [142][116]. For this reason, motor treatment is inevitable. The costs of stroke and post-stroke treatment are estimated at USD 73.7 billion in the United States of America and USD 64.1 billion in Europe [70][116].

Post-stroke patients typically can suffer from limb impairment, imbalance disorders, visual impairment, aphasia, cognitive disorders, and problems with maintaining the body in an upright position [116]. The rehabilitation process is an integral part of the treatment and should be introduced at an early stage if there are no contraindications. According to modern medical practices, patients should be treated as if they are to restore all their functionalities [102].

Post-stroke rehabilitation contains the following activities [131][116]:

- taking care of the appropriate laying patient's position to avoid contractures and bedsores (at the early stage);
- anti-clotting respiratory exercises (at the early stage);
- physiotherapeutic exercises - initially simple passive single joint activation and then targetting active (from the early stage);

- gait reeducation (at later stages);
- muscle tone normalisation (at later stages);
- increasing muscular force by resistance treatment (at later stages);
- eliminating incorrect motion patterns while exercising (at later stages);
- task-oriented exercising.

Post-stroke kinesiotherapy is a relatively intensive process. It typically requires a few hours of exercising daily in sessions of around 60 minutes each [131] that take years, with the window critical for recovery of the first 3-6 months poststroke [21]. Due to this and the motion limitations of patients, home-based physiotherapy is superficial in post-stroke cases. For this reason, dedicated tools, including games, robots, VR and additional sensors, are developed [32].

1.3.2 Other neurological disorders recovery process

Neurological disorders other than stroke also affect the motor capabilities of a human. Among others, these include [84]:

- amyotrophic lateral sclerosis
- dystonia;
- muscular dystrophy;
- myasthenia gravis.

They are described below with descriptions of possible physiotherapy approaches.

Amyotrophic lateral sclerosis is a disease that affects central or peripheral motoneurons. The most severe effect of such can be a full-body impairment. The disorder is diagnosed mainly based on the EMG signals, as then the muscular tissue tends to have irregular and decreased electric activity [84]. Amyotrophic lateral sclerosis is typically tackled with pharmaceutical treatment. However, physiotherapy is critical in its early phase to maximise the functionality of a patient. Therefore, it should be focused on task-oriented exercises and increasing the force of the weakened muscles. At the later stages, more palliative care with the exercises mobilising impaired limbs is needed [94].

Dystonia is a disease that results in unintended convulsive movements or incorrect positions of body segments caused by unintended muscle contractions. These are treated pharmacologically, or with the deep stimulation of brain [84]. Patients with such disorders can benefit from kinesiotherapeutic exercises aimed at recovering voluntary control of the affected body parts or developing compensatory movement strategies [118].

A muscular dystrophy is a group of diseases affecting patients' muscles. In general, it can result in muscle contractures, decreased muscular force or even flaccidity. The medical examination often includes EMG measurements, as the electrical activity of muscles is irregular [84]. Performed physiotherapeutic exercises should aim at maintaining the available motions and recalling functionality of the body segments, particularly extremities [44].

Myasthenia gravis is an autoimmunological disease resulting in increased tiredness of muscles and hence, their weakening. It is treated with medicines, including steroids. However, patients can benefit from physical exercises with the appropriate resting periods. These should be targeted in increasing the fatigue resistance of the organism [36].

Moreover, the treatment of diseases affecting not only muscular endurance but also control over muscles brings positive neuroplastic effects. Therefore, the task-oriented approach is critical for such cases [151].

1.3.3 Orthopaedic diseases recovery process

Orthopaedic rehabilitation is a process of recalling functions lost due to orthopaedic diseases, both congenital and acquired or injuries. The latter is typically the result of accidents. Hence they are described in the next subsection.

Rehabilitation in orthopaedic cases aims to correct the range of motion and ease the pain connected with the disease. The common orthopaedic illnesses which benefit from physiotherapy are arthritis and osteoporosis. The first one is a disorder of joints which causes their pain, swelling, and limited movement. It can benefit from kinesiotherapeutic exercises by increasing mobility and mobilising them to prevent further damage [40]. The second one, osteoporosis, is an illness causing progressive bone loss and hence, skeleton fractures. It is a common problem among elderly people. The therapy with motion is used to increase bone density due to the resistance treatment and to increase the balance ability of patients to prevent hazardous falls [113][104].

1.3.4 Post-accidental recovery process

Accidents are the common causes of soft tissue disruptions and bone fractures. These result in the immobilisation of certain body segments and their weakening [117]. In the most severe cases, the spinal cord can get injured, which leads to serious motion system impairment. The accident-related cases are typically connected with traffic accidents, falls from a height, sports injuries or gun-related injuries [101].

Depending on the severity of the impairment, either single functions are temporarily restrained (e.g. as for the bone fractures in extremities) or full-body paralyses can appear. Therefore, the treatment should be adjusted to the individual conditions.

Lighter injuries medical treatment should be followed with physiotherapy containing [117]:

- kinesiotherapeutic exercises - optimally active;
- increasing muscular force by resistance treatment;
- task-oriented exercising.

Severe cases should be followed with physiotherapy containing [101]:

- taking care of the appropriate laying patient's position to avoid contractures and bedsores;

- stretching exercises;
- kinesiotherapeutic passive exercises aiming at joints and soft-tissues mobilisation;
- kinesiotherapeutic exercises, aiming at keeping the chest region movable.

1.4 Remote home treatment

The concept of remote home treatment emerged particularly during the COVID-19 pandemic when many patients were restricted from participating in regular physiotherapy sessions [15][37]. It aims to provide rehabilitation services in a home environment without the need for physical interaction between patients and medical professionals [37]. However, the lack of the therapists' physical presence brings additional challenges. Some of these are related to legislation regulations [37], likewise for other not yet widely implemented innovations. The others are strictly connected with the performance of the system. As for conventional treatment, telerehabilitation includes examinations and interventions, which in some cases require the force-support of a physiotherapist [15]. Moreover, distant collaboration brings the need for a stable and safe remote connection [37]. These can be solved with the use of appropriate engineering tools.

Therefore, the delivery of distant healthcare requires additional ICT technologies and possibly also additional mechatronic devices [37]. An approach to performing remote home treatment varies depending on the health conditions of a patient. Hence, this can require significantly different equipment as well. For patients with less severe conditions, teleconference-based therapy or simple software systems can be sufficient [37][73]. On the contrary, some may need more advanced tools, such as smart wearables or advanced physically supportive devices [20]. The wide range of possible approaches can make the therapy suitable for almost anyone. However, not every tool is suitable for each case.

For this reason, the considered types of solutions were analysed in terms of their advantages and disadvantages; particularly for the target group of post-stroke or post-accidental patients and people with orthopaedic diseases. The results are presented in table 1. As providing the treatment with the anatomical motion pattern is critical for the considered medical cases, the devices without the precise guidance of all extremity joints are treated as inferior.

Table 1: Considered tools for remote home treatment.

Tool	**Advantages**	**Disadvantages**
Mobile application	- Low cost; - Simple in use; - Engaging; - No room requirements; - Possible to use anywhere	- No controlled guidance of extremity; - No force support; - Not a medical device; - Difficult to use for elderly people
Kinect-type game	- Relatively low cost; - Based on the developed solutions; - No room requirements; - Engagement	- Low accuracy; - No force support; - Not a medical device; - Difficult to use for elderly people
Small wearable devices	- Lightweight; - Low cost; - Relatively simple in use; - No room requirements; - Possible to use anywhere; - Possible to integrate with other systems	- Low accuracy; - No force support; - Not engaging without additional tools used
Rehabilitation manipulator	- Complex rehabilitation possible with a single device; - High accuracy; - Force support; - No requirements for complicated dimensional adjustments; - Medical device	- Large and heavy; - Expensive; - Room requirements; - No precise guidance of a whole extremity; - Not engaging without additional tools used; - Complicated to implement
Rehabilitation exoskeleton	- Complex rehabilitation possible with a single device; - Precise guidance of the whole extremity; - High accuracy; - Force support; - Possible to use by patients with muscle flaccidity; - Medical device	- Requirements for complicated dimensional adjustments; - Expensive; - Not engaging without additional tools used; - Complicated to implement
Functional EMG	- Possible to use by patients with muscle flaccidity; - No room requirements; - Medical device	- Low accuracy; - Not engaging without additional tools used; - Complicated to implement

Based on the advantages and disadvantages presented in table 1, exoskeletons are the most suitable solutions for remote home treatment. This is due to their relatively compact size, accuracy in monitoring and direct mobilisation of DOFs. Moreover, their construction enables further minimisation and application as assistive robots. Nevertheless, exoskeletons can be enriched by combining them with other tools, such as games and systems for biosignal monitoring or stimulation. Thanks to this, patients' engagement can be kept at a constantly high level, and their performance can be monitored even more precisely.

1.5 Robot-aided rehabilitation

The application of robots in rehabilitation is targeted at either supporting the recovery process or substituting missing functionality of a patient [107]. The approaches to this process, and hence the used devices, can differ from one another. Therefore this subsection includes a general description of the robot-aided physical rehabilitation process and the applicable robots.

1.5.1 Methodology

Most of the devices used for motor rehabilitation include a moderate level of interface with the human body. Hence, they are rather end-effector robots than wearables [107]. However, there are also devices used for physiotherapy, more complex in terms of human-machine physical interaction [35][145].

For both, the treatment can be realised in either assistive, active or passive modes [107]. The first approach requires the voluntary activity of a patient, which then can be supported by the robot (e.g. by gravity compensation). Active rehabilitation is either acting in line or against the intended trajectory to support or resist the motion. The device measures the performance of a user in real time and supports motion only if needed. On the contrary, passive therapy can be realised even for flaccid objects, as the device fully overtakes duties. The nomenclature used to describe possible approaches corresponds to the one used for conventional therapy with human-physiotherapist support [107].

In general, kinesiotherapy with the aid of robots is realised as repetitive following the given trajectories. For such applications, the stiff mechatronic devices are superior to humans [153]. The main differences between the rehabilitation systems arise from the modality used, the kinematics of the devices, and additional ICT technologies involved in the process.

Apart from passive therapy, robot-aided treatment includes a human in the feedback loop [107]. Therefore, their mechanical parameters need to be monitored. This has to cover kinematic and dynamic parameters of the physical system - either by measuring joint rotations and their derivatives or positions of characteristic points, and the forces occurring there [153]. Such measurements are conducted during the whole exercising session.

1.5.2 Market of rehabilitation devices

The global market of rehabilitation devices is valued at around USD 20 billion with a CAGR of 5.9%-6.09% [78][95][121]. It is more fragmented than consolidated [78]. Therefore, new companies are emerging despite high financial entry barriers. It is developing the most in Asia and Australia [78]. Regarding Europe, central and highly-developed countries (e.g. Germany, France, Switzerland, Netherlands) represent the lowest growth rate of the rehabilitation equipment market [78].

The market of robots for physiotherapy is smaller but reaches more than USD 1.5 million with a much higher CAGR of 22.1% [77]. Worth noticing is the fact that exoskeletons are responsible for almost half of the marker, as a relatively new and promising technology [77].

1.5.3 Devices for robot-aided rehabilitation of extremities

There are numerous robots for the rehabilitation of extremities, both end-effector manipulators and exoskeletons. Therefore, a review of existing and developed solutions was prepared to investigate the capabilities of robot-aided therapy for remote home use. The selected devices for the upper and lower extremities were assessed in terms of their mobilisation method and realised motion, masses, dimensions, dimensional adjustability, and additional ICTs integrated. The ICTs were selected as the key factor for therapy automation, safety monitoring, and engaging patients. The published paper, including this analysis, is presented in the original research paper correlated with this thesis (see appendix A[58]). As exoskeletons enable direct support and monitoring of DOFs in human joints, they seem to be the most appropriate tool for precise kinesiotherapy. Moreover, they usually do not require large room space to exercise and can be used for post-physiotherapy recovery support of the motion. Moreover, the use of exoskeletons results in more natural motion patterns [67]. However, they also have their disadvantages.

1.5.4 Challenges in exoskeletons implementation

Exoskeletons, apart from the benefits of using them in the rehabilitation process, come with significant challenges. Compared to the end-effector robots, they currently require more work from operators [62]. This is due to their weight, safety issues from immobilizing a patient to the braces, and the need for dimensional adjustments [62]. Moreover, their structure parallel to the extremities results in the requirement for precise length adjustment of the devices. The misalignments between exoskeletons and human joints can result in discomfort, pain or even tissue damage [23]. Furthermore, devices that do not enable full joint activity may exclude patients with muscle contractures from the therapy. This is due to the fact that such patients can be not able to reach a neutral position with their range of motion. Hence, their extremities cannot be attached to the described

exoskeletons.
Even though exoskeletons can be particularly advantageous in the therapy of people after severe spinal cord injuries [67] and post-stroke patients [122][96], they are not often used. This is due to the lack of clinical trials proving their efficiency [62].
A solution to these problems should comprise of the following:

- Minimising the weight of the device while conserving its capabilities;
- Adapting the device to real-life use by providing additional ICTs for safety monitoring;
- Conducting experiments to prove the superior performance of such systems.

1.6 ICTs in rehabilitation

The ICTs' involvement in rehabilitation is a topic that still requires investigation [154]. They are particularly applicable to neurological treatment if they are designed with an appropriate approach [154][34][71]. In rehabilitation, ICTs contribute to the faster information flow between a patient and a healthcare system [71]. The data are also better organised and easier reachable from any place [71]. Thanks to these, effective personalised cognitive therapy is possible [34]. However, this is true only while meeting the four main criteria [34]:

- Supporting complex activities of daily living (ADLs);
- Automatic errors detection;
- Home use effectiveness;
- Accessibility.

Nevertheless, only 33% of European projects fulfilled all of these requirements [34]. Therefore, the designed solutions should comprise tools for task-oriented home treatment, enabling safety monitoring and patient engagement, but at the same time remain available to the users. Based on the analysis of current trends, a need for developing systems for in-house use and validating their automatic performance is necessary. The following presentation includes AR, VR, MR, XR, EMG, EEG, FES, AI, mHealth and telemedicine as the leading ICTs to be used in kinesiotherapy.

1.6.1 AR, VR, MR, and XR

Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR), and Extended Reality (XR) are techniques of deeply immersive projection. Research proves that using these with serious games for motor rehabilitation helps patients reduce their perception of pain and motivate them to exercise more [28]. As these methods suffer mainly from inaccurate sensory systems, combining them with rehabilitation robots solves these problems [28]. Virtual reality and its other presented alternatives are proven to be less stressful than conventional kinesiotherapy [28]. They are effectively used to visualise desired motion in almost real time. Hence, to make it immersive, the applications remain rather simple so as to resemble real extremities. Moreover, these technologies are applicable for task-oriented treatment by incorporating repetitive motion into games [41][64]. However, using even light and adjusted VR googles and controllers may be difficult or have undesirable side effects on neurological patients, post-stroke in particular [82][47]. Apart from the possible side-effects and lack of accuracy in VR, AR, MR and XR vision-based systems, these methods' disadvantages are also high costs for individual patients and lack of dedicated solutions with medical certifications [28]. However, applications for VR/AR goggles are being introduced to physiotherapy under the supervision of specialists.

Furthermore, despite their advantages, the presented technologies are not yet commonly involved in distant kinesiotherapy of people with severe impairments. The use of VR for telerehabilitation is occasionally considered with mechatronic devices, and haptic controllers, which increase the overall price and do not provide real-live sensation stimuli [25]. For the latter reason, the application of such technology in line with complex rehabilitation robots can synergy possible outcomes.

1.6.2 Biosignals tracking and FES

EEG and EMG are the most popular techniques for collecting biological signals for further analysis or even for automating motor therapy. The former is the analysis of brain electrical activity, while the latter is dedicated to skeletal muscles. Both can be performed with the needle electrodes or recorded from the surface of the skin. The second approach is more frequently used for rehabilitation and sports applications [27].

Both techniques are interesting for researchers working on automating motor treatment. However, they are usually used separately, mainly for diagnosing purposes or one of the analyses complementary to the other [27][80]. The usage of combined analyses is seen as a breakthrough in robotic rehabilitation [27]. If conducted well, it can significantly outperform analysis based on a single type of signals [80][137]. Thanks to this, the device could faster adapt to the patient and select the adequate exercise programme [89].

As the EMG is currently a mature technique, it is investigated in terms of potential real-time application [89]. On the contrary, EEG's robust applicability is yet not experimentally confirmed [89]. Nevertheless, it remains a promising investigation field, especially due to the low delay of processing [122][89]. Worth considering is the fact that the researchers analyse the capabilities of biosignal tracking control cycle in studies with exoskeletons [149][126][89][129][46][140][112][85][91]. This means, that these techniques can be used to sense movement intentions of the users [89] and potentially monitor hazards during the therapy [147][148]. An extended study of requirements regarding safety systems for teleoperated rehabilitation devices was performed (see appendices J and K).

Apart from skeletal muscle activity tracking, electrical stimulation is also possible. FES is based on stimulating muscles not controlled by the central system by an external electrical trigger to contract. This technique is used during the treatment to increase the energetical expenditure of patients and exercise more naturally [67]. Moreover, it is safer than mobilizing the joints externally [39]. On the other contrary, it is relatively difficult to apply in robot-aided treatment due to the nonlinearity of muscle operation[67]. Nevertheless, it is a promising subject of research on hybrid control [18][122]. FES technology is mainly investigated during gate training [18][114][76][43] and rarely for the kinesiotherapy of upper extremities [33][122]. However, it can be particularly beneficial for reaching natural motion patterns in motor therapy with lighter devices by stimulating weaker tissues and restraining the activity of the stronger ones [18][122]. Moreover, its effects, while combined with rehabilitation robots, are superior compared to the results of only robot-aided treatment for severely disabled [122].

1.6.3 Artificial Intelligence

Artificial Intelligence (AI) is a technology used in rehabilitation, and particularly physiotherapy [133], for four main purposes [128]:

- prevention;
- diagnosis;
- treatment;
- prognostication.

The first area is dedicated to the early detection of potential risky factors of certain disabilities and further monitoring of their progress [128]. This is similar to diagnosis with the difference that the latter is performed on the patients with symptoms and targeted at finding the appropriate treatment for them [125]. The patients can be diagnosed more precisely based on the big data, also containing elements not typically used for particular cases [125][75]. The machine learning (ML) algorithms can also contribute to predicting the effects of the whole treatment [72][13][124]. This is applicable at different stages of the rehabilitation - either prior to intervention or once the process is completed[124]. All of these are possible due to AI's capabilities to take decisions based on big data. These can be even more reliable than qualified physiotherapists'. However, it is most beneficial to combine human flexibility with the analytics of the numerical models [88].

Within the treatment, AI is typically used to monitor patients' performance and health conditions [100][152][128][88]. This benefit from using combined biosignals, tracked kinematic joint parameters [100] or even facial expressions and eye motion [128].

AI is also a powerful tool to support control over the interaction of rehabilitation robots with patients. Thanks to its application, biomedical mechatronic devices can learn how to perform their duties more naturally. This can be realised by either sensing patients' intentions and reacting to them with a certain approach [29] or learning genuine patterns of performing tasks and emulating physiotherapists' behaviour [61]. Moreover, the nonlinear physical models can be substituted with the learning algorithms [141]. Thanks to this, the inaccuracies from the differences between the real world and its numerical representation can be reduced. The control methods based on models involving artificial neural networks (ANN) are promising to be effective for hard exoskeletons [141].

1.6.4 Telehealth

With the development of telephones, new concepts of their use for healthcare are developed. This technology, known as telehealth, addresses the need for service gaps, urgent issues, or mandated services [146]. During the COVID-19 pandemic, its significance increased due to common restrictions for stationary services [63][105].

Telehealth technologies include telemedicine and mHealth. The former is the application of communication technologies for distant real-time consultation with doctors [81]. Thanks to this, patients can be treated more quickly by experienced professionals. Due to the increase in the number of smartphone users, applications dedicated to all life applications emerged. This also includes medicine and, specifically, rehabilitation [154]. Applicability of mobile phones and other small smart devices, such as smartwatches for diagnosing, treatment or prevention, is called mHealth. There were over 350,000 mobile health apps available in all the app stores in 2021 [12]. Compared to telemedicine, mHealth is targeted rather at self-use [81].

The telehealth tools enable more intuitive and accessible methods of questionnaire-based self-diagnosing, health monitoring with the use of smart devices, remote consultations, or even gamifying the treatment [60][146]. The latest brings new opportunities for treatment visualisation, particularly applicable to motor telerehabilitation. This is the trend of the future, which complies with IoT with the common use of neural networks. Moreover, it enables workouts customisation while maximising their effectiveness without overly engaging specialists. Apart from generating automatic treatment patterns, such systems enable automatic assessment of progress based on measurable signals [106]. The outcomes of motor and neurological telerehabilitation can be, in general, compared with in-person treatment [127]. This also corresponds to severe motion impairments and relates to measurable progress and satisfaction of patients [19].

Besides the presented advantages, real-life applications of telehealth meet the following limitations [63]:

- technology exclusion or unavailability;
- privacy and data-related policies;
- need for physical intervention or diagnostics with specialist devices;
- lack of medicians' technical;
- need for personal interaction between a human and a doctor.

Hence, for now, simpler tools combined with mechatronic devices enabling physical intervention or specific should be developed. Simultaneously, the medical staff must undergo training programmes to get familiar with the technologies. At the same time, the works on corresponding legislation and telehealth guidelines have to be conducted. Moreover, the global south should be supported in increasing their technological access [105].

1.6.5 Digital twins

Digital twins are the computational representations of real-life objects, e.g. organisms. In healthcare, they are typically used to monitor patients' health conditions. Substituting human observation-based assessment by constant monitoring with various sensors and using the gathered data in simulation models. By application of this approach, it is possible to reduce risks for patients [143] and automatise treatment [65]. Moreover, in robot-aided rehabilitation, the interface between the device and a user can be modelled as well and then used to analyse its biomechanical impact [24]. Such data can be used to predict potential hazards and eliminate them prior to their occurrence. The concept of such a solution and the review of current applications of digital twins in medicine and robotics are presented in the original research paper correlated with this thesis (see appendix E [57]). Apart from the clear benefits, digital twin technology mainly suffers from computational costs of complex models, inaccuracies in biomedical models and latency in cyber-physical systems.

1.7 Summary

This section presented methods and medical cases typical for physiotherapy. The descriptions included methods of exercising and limitations for patients. Based on the defined challenge, possible tools for counteracting the problems were mentioned. Based on their capabilities, the exoskeletons with additional ICT packages were selected as the most appropriate. Their applicability and effectiveness in the therapy is investigated in the further sections of the thesis.

2 Project details

2.1 Introduction

The following section is dedicated to presenting the basis of the topic taken up. This contains a description of the gap detected in the scientific state-of-the-art and commercially offered systems, the needs of the customers and users, formulation of the thesis and planned tasks, as well as design intent. All of these characterised precisely, enable work on the goal and assessment of obtained outcomes.

2.2 Motivation

World Health Organisation informed in 2011 that almost 15% of people are affected with some form of disability [108]. This complies with the results of current data from other reports [99]. Thus, the problem of people who require rehabilitation is significant and does not decrease in terms of numbers. The motor treatment is particularly important for neurological patients, post-stroke, among others. 70% of them suffer from upper extremity impairment, while 88% are affected with hemiparesis, which results in gait disorders. Not only do these require intensive kinesiotherapy, but they also have limited capabilities of commuting to specialist clinics. This combination can be particularly problematic for inhabitants of rural areas or those not living with the care of their family members. Moreover, with the pandemics of COVID-19, a need for treatment without the physical presence of physiotherapists emerged [119]. During emergency situations such as mentioned outbreaks of diseases, wars, or natural disasters travelling to medical centres may not be possible. This may affect regular workouts and decelerate the convalescence period or even restrain its results. On the other hand, the number of professionals in the field of rehabilitation is not sufficient. The global needs exceed capabilities in this field by ten times [109]. The major pain of Polish patients is the time of waiting for the diagnostics and consultations with professionals [5]. Moreover, the time spent on physiotherapy is outstandingly too short. It is 22.5 minutes per patient in Poland, while the European average is 52 minutes per trauma [98]. Companies such as *EGZOTech* prove that robots may be used to compensate for insufficient human resources. 250 *Luna* robots have been applied in medical centres, where some of them use small fleets of these operated simultaneously by one physiotherapist [98]. The presented problems may be addressed in general with the application of rehabilitation robots. With these, the therapy may be transferred to the patients' houses and provided with a minimally supervised approach. Nevertheless, commercial systems mobilising multiple joints are not available enough due to their prices. Moreover, many rehabilitation devices do not provide sufficient direct mobilisation of joints and monitoring systems [15]. Without these, supervision of patient performance and safety may not be realised without additional feedback channels, e.g. video cameras. Also, even though visual observation may be supplied, it does not enable the physical correction of registered defects in motion patterns. Rehabilitation robots may contribute to the treatment of neurological patients [115] and be applied even for complex mobilisation of multiple degrees of freedom [134]. For such diseases, it may be effectively applied for therapy of upper extremity [107], which is often an object of task-oriented exercises. Rehabilitation robots' most foreseen application for the future is home use within minimally supervised therapy [119]. So far, the devices offered for the market do not enable such functionality. Therefore, uptaken works focused on the design of a rehabilitation system for remote home use and proving that the selection of ICTs can contribute to safe and engaging therapy.

2.3 Goal

The main challenge of the doctoral thesis is to prove that remote kinesiotherapy of the patient's upper extremities is possible with a robot-aided system supported by selected ICT technologies. This goal is realised by designing and building a prototype of the exoskeleton dedicated to such an application and connecting it with EMG tracking and a VR environment. These two are combined with the control system and human-machine interface and aim at therapy automation, visualisation of treatment data, and entertaining the patient. The research should be finalised by meeting three main criteria:

- Building a lightweight exoskeleton for task-oriented kinesiotherapy of the upper extremity;
- Implementing EMG into control of the system and VR into patient's visualisation of treatment;
- Assessment of these technologies' measurable impact on patients' biomechanical performance.

2.4 Thesis

Regarding the aspects presented above, the thesis is dedicated to proving that robot-aided rehabilitation systems with the selected ICTs are applicable to the home-like environment with minimum supervision of the physiotherapists. For this reason, the following theses were selected to be confirmed:

1. The rehabilitation exoskeleton loads the musculoskeletal system of the patient comparably to the physiotherapist;
2. Use of the VR/AR motion visualisation provides better accuracy of motion-path following.

2.5 Scope

To address the problem and achieve the described goal, the following fields need to be covered:

- In-depth identification of the need;
- Modelling task-oriented kinesiotherapy sessions;
- Kinematics and dynamics simulations of the system;
- Mechanical and electronic design;
- Construction of the exoskeleton;
- Development of the control system and an HMI;
- Designing EMG tracking system;
- Implementing EMG tracking for performance assessment;
- Building a VR application for visualisation of the treatment;
- Implementing VR for the treatment;
- Experiments on patients' biomechanical performance;
- Validation patients' individual perception and side effects.

The other fields required to prepare a market-ready solution or application of any other ICTs are not included in this thesis. However, these will be the subjects of other R&D projects, being the offspring of this work. The chosen ICTs were selected as the ones enabling safe operation under the minimal supervision of physiotherapists and immersive presentation of the exercises to the patient. Thanks to these, the therapy could be transferred to fully remote.

2.6 Design intent

The system must be compliant with the law regulations and functional requirements towards the remote home rehabilitation device. The following set of design intents reflects these in a measurable way. All the mechanical parameters were calculated based on simulations presented in the following sections but presented here to summarise criteria in a measurable way. The developed kinesiotherapeutic system should have the following characteristics:

- Attachable to the back and shoulder girdle of a patient or to the additional frame/chair;
- Maximum of 10 kg without control cabinet and frame;
- Adjusted to the neurological (post-stroke, among others), orthopaedic, post-trauma, and post-surgical patients;
- Adjustable to the dimensions of users between 5^{th} Polish female centile and 95^{th} Polish male centile [66] with measurement of the shift with minimum 1 mm precision;
- Passive and active treatment with either force support or resistance;
- Adjusted to the task-oriented treatment;
- Enabling full mobilisation of the shoulder (three DOFs) and elbow (two DOFs) of one extremity according to the ISOM standard [69];
- Axes of the DOFs related to the single joint intersecting in one point;
- Three driven DOFs (two in shoulder and one in elbow) with corresponding minimal parameters (torques and angular velocities for the DOFs counted from proximal to

distal) and encoders of at least 0.2° accuracy:
  - first driven DOF: 43.2 Nm/-140°/s,
  - second driven DOF: 43.2 Nm/140°/s,
  - third driven DOF: 7.6 Nm/140°/;
- All drives supplied with electrical power;
- Two free DOFs as plain bearings with encoders of at least 0.2° accuracy;
- Remote almost real-time treatment monitoring;
- Remotely adjustable treatment parameters;
- Simple interfaced provided with a touch-screen operator panel or via the app available remotely;
- Connection to the WiFi or mobile network and the minimum bandwidth of 10 Mbps (measured with the dedicated software);
- Power supply from the 230 V socket or a battery;
- Available to attach optional ICT packages (initially 12-channels EMG and VR visualisation) - easy option to extend electrical inputs to at least 200;
- Designed to be used 6-8 h per day, seven days a week, in the 0.5-2h cycles;
- Dimensions of the exoskeleton itself packed for transport not exceeding 500x500x1000 mm;
- Compliant to the standards of the medical device IIa category [8];
- Compliant to the following standards:
  - ISO 13485:2016 - Medical Devices Quality Management System;
  - ISO 13482:2014 - Robots and robotic devices — Safety requirements for personal care robots;
  - ISO 14937:2009 - Sterilization of health care products — General requirements for characterization of a sterilizing agent and the development, validation and routine control of a sterilization process for medical devices;
  - ISO 14971:2019 - Medical devices — Application of risk management to medical devices;
  - ISO 20417:2021 - Medical devices — Information to be supplied by the manufacturer;
  - ISO 22523:2006 - External limb prostheses and external orthoses — Requirements and test methods;
  - PN-EN 60601 - Medical electrical devices (including: EN 60601-1:2006, EN 60601-2-10:2000, EN 60601-1-11:2010, EN 60601-1-6:2010, EN 60601-1-4:1996 and EN 60601-1-1:2001);
- Compliant to the norms F48 published in *Annual Book of ASTM Standards* [42];

By meeting these, the exoskeleton is able to be used by a patient supported only by their closest relative, mobilise the extremity within its full anatomic range, as well as provide an opportunity to track progress based on sensory systems and enable adjusting the treatment from a distance.

2.7 Summary

This section presented the motivation, goal, thesis, and scope of the project, as critical in terms of scientific research and project management. The overall aim of the project is to start the design process of the rehabilitation exoskeleton dedicated to being used as a medical device and assess the usefulness of selected ICTs. However, this thesis will not result in the final product. Its side aim is to prepare the basis for further R&D projects submitted to the granting authorities by the researcher. Nevertheless, the exoskeleton integrated with the VR system and EMG measuring systems is planned to be sufficient to be used as the object for initial experimental trials according to the presented theses.

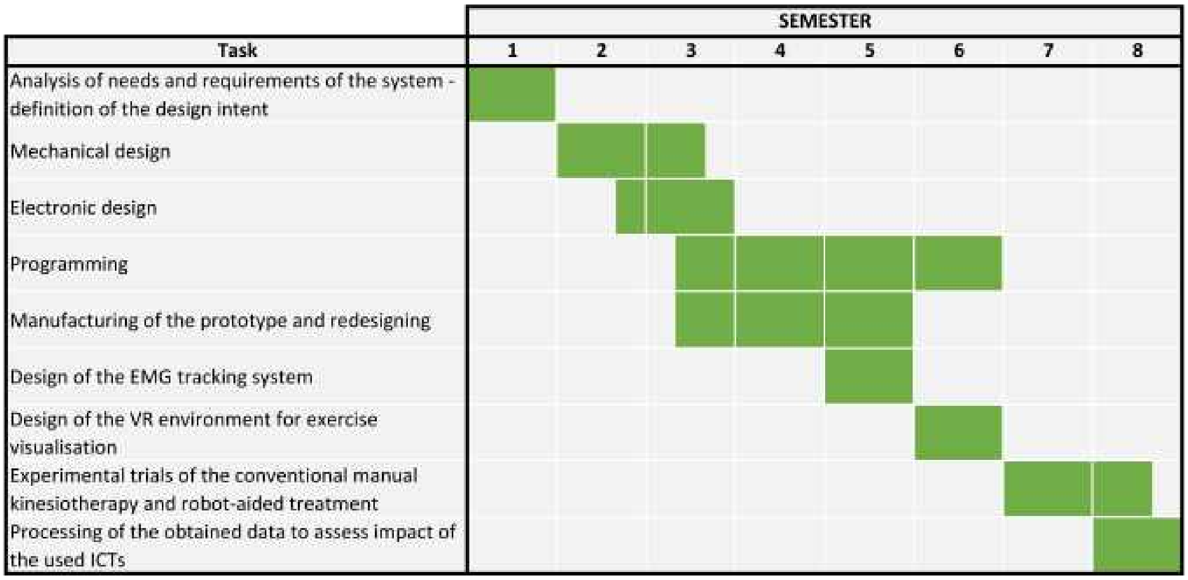
3 General methodology

3.1 Introduction

The following section presents the workflow, general methods and tools used for this thesis. These do not contain precise descriptions of methods used for every technology (e.g. control or filtration algorithms). Such detailed data are presented in the subsections dedicated to particular technologies. The information in this section aims to set the time-management and technological work frames for the whole project.

3.2 Workflow

The work plan contains the following core tasks realised within four-year research. They are presented with their real times of realising in figure 1.



	SEMESTER							
Task	1	2	3	4	5	6	7	8
Analysis of needs and requirements of the system - definition of the design intent	🟩							
Mechanical design		🟩	🟩					
Electronic design		🟩	🟩					
Programming			🟩	🟩	🟩	🟩		
Manufacturing of the prototype and redesigning			🟩	🟩	🟩			
Design of the EMG tracking system					🟩			
Design of the VR environment for exercise visualisation						🟩		
Experimental trials of the conventional manual kinesiotherapy and robot-aided treatment							🟩	🟩
Processing of the obtained data to assess impact of the used ICTs								🟩

Figure 1: Workflow of the development works and research.

To assess the completeness of the presented works, the following milestones were formulated:

- Defined design intent to the exoskeleton with the specified relevant standards (by the end of semester 1);
- Full mechanical and electrical design of the first prototype (by the end of semester 3);
- First prototype of the exoskeleton manufactured and assembled (by the end of semester 4);
- EMG tracking system integrated with the control system of the exoskeleton (by the end of semester 5);

- VR-based treatment visualisation interface integrated with the control system of the exoskeleton (by the end of semester 6);
- Experiment plan with an obtained corresponding approval of the bioethical committee for the planned trials (by the end of semester 6);
- Completed trials comparing manual kinesiotherapy and robot-aided treatment with the selected ICTs with the analysed data - confirmation or rejection of the stated theses (by the end of semester 8).

3.3 Methods and frameworks

In general, Computer-Aided Design software (CAD) is used to design while Computer-Aided Engineering software (CAE) is used to validate the performance of the mechanical and electrical subsystems of the exoskeleton. Moreover, as the device is manufactured mainly with additive methods, Computer-Aided Manufacturing software (CAM) is involved in preparing trajectories for the 3D printers.

The control algorithms and tracking systems are initially simulated and then programmed. The latter is realised at a microcontroller in *C* and a microcomputer in *Bash* and *Python* with the use of *ROS* environment. VR systems are integrated with the previously prepared control systems by the communication nodes and designed graphically in the *Unity 2020.3.34f1* software.

Precise methods are described deeply in the corresponding sections. However, table 2 presents the used frameworks with their applications.

Table 2: Frameworks used in the development works and the research.

Application	**Framework**
Mechanical design and basic strength analyses	Autodesk Inventor Professional 2020
Electric and electronic design	AutoCAD Electrical
Complex multibody dynamics simulation	Adams 2021.1
Complex strength analyses and a structural optimisation of selected components	ANSYS 2021 R1
Computing needed torques for motors selection	Matlab R2021a
Generating g-codes for the 3D printer based on the mechanical models of small components	PrusaSlicer 2.5.0
Simulating and testing control algorithms	Matlab R2021a
Simple multibody dynamics simulations	Simulink
Programming the STM microcontroller	STM32CubeIDE (C)
Exporting registered trajectories and biosignals	STM Studio
Controlling motors and communicating with peripheral systems; synchronising systems	Raspberry Pi OS (Python)
Launching the pipelines of programs	Raspberry Pi OS (Bash)
Integration with a digital twin and communication with external devices	ROS
Designing the VR environment for visualisation of the treatment	Unity 2020.3.34f1

3.4 Summary

This section included a description of the plan for the research in terms of its stages as well as involved methods and tools. It helped in tracking the progress and planning the apparatus required to perform sequential stages. Moreover, these settings formed the base for planning precise methodology described in the following sections.

4 Design of the system

4.1 Introduction

The following section is dedicated to presenting the construction of the exoskeleton for the upper extremities prototype designed and built for the experimental procedure. This contains a description of pre-design analyses, mechanical design, electronic design, control system, human-machine interface and the considered rehabilitation routines. The prototype system fulfils the first project goal and enables further investigation of the ICTs' applicability.

4.2 Users' needs

Prior to the design of the device, an investigation of potential end-users and customers was conducted. It consisted of separate examinations of needs for the groups of physiotherapists and patients. The former was started with three in-depth interviews to formulate the research questionnaires and then followed by the online survey of 138 Polish professionals. Its results were described in the original research paper (see appendix B [56]). The latter was based on an online survey of 60 people who experienced kinesiotherapy of any extremity. Unfortunately, the answers gathered were inconsistent. Hence, only the outcomes of the primary investigations were considered relevant. These became the base for the design intent. As the device aims at solving problems of rehabilitation, the following mentioned challenges are critical:

- difficulties in the measurable and universal assessment of patient's progress;
- keeping high motivation of a patient getting bored or tired;
- commuting between patients' houses and medical centres for both patients and physiotherapists (particularly important during the COVID-19 pandemic, as an extensive number of remote solutions was developed);
- physical tiredness related to lifting and supporting patient's body segments.

4.3 User flow

The system is designed to be used at non-medical facilities, such as fire stations or community centres, under the minimal remote supervision of a physiotherapist. However, this does not necessarily have to be in the house of the patient. Once the device is supplied and installed in such a facility, the intended user flow should consist of the following steps:

1. onsite design of a single rehabilitation session by the physiotherapist:
    - medical interview and health qualification;
    - dimensional adjustment of the device;
    - measurement of the patient's ROM;
    - recording motion trajectories;

    - setting type of the treatment;
    - validation trial continuously-monitored rehabilitation session.
2. preparation for the next session:
    - automatic design of the next rehabilitation session (including ROM assessment);
    - possible manual changes by the physiotherapist in the designed routine;
    - scheduling the next session for both the physiotherapist and the patient.
3. rehabilitation session:
    - launch of the system;
    - attachment of the patient's shoulder girdle, arm, forearm, and wrist to the exoskeleton by the qualified operator (non-medical stuff);
    - selection of the prepared routine;
    - main treatment
        - visualisation of the desired trajectory with supporting or resisting the patients' motion mobilising multiple DOFs simultaneously,
        - automatic performance and safety monitoring based on the measurements (including immediate emergency stop if needed);
        - minimal remote supervision of the physiotherapist operating multiple devices simultaneously;
    - unattachment patient's body segment from the device.
4. follow-up assessment:
    - progress assessment;
    - visual presentation of results to the patient;
    - storing recording data into the patient's private database;
    - sending results to the physiotherapists for follow-up diagnosing;
    - coming back to the preparation for the next session if planned.
5. periodic assessment of the health conditions:
    - decision on whether to continue the treatment with the device;
    - implementing changes in the rehabilitation routine if needed;
    - coming back to the preparation for the next session if planned.

The scheme of the rehabilitation from the prescription of robot-aided kinesiotherapy to the end of this process is visualised in figure 2. Implementation of the designed exoskeleton can reduce the time spent on the convalescence process by the physiotherapist by automating it. Thus, the professional can focus on diagnosing more patients at the early stage of their health issues.

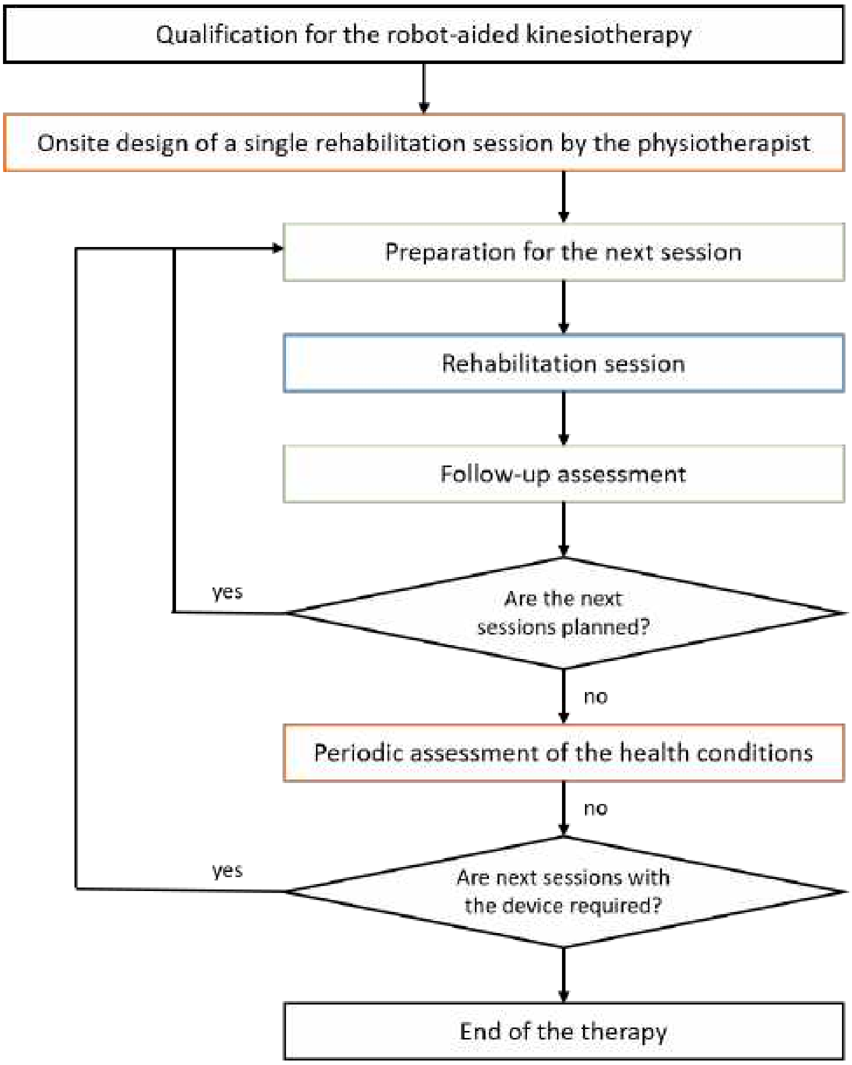


Figure 2: Scheme of the user flow (stages involving meeting of physiotherapists with patients bordered by orange, the stage involving minimal remote supervision bordered with blue, and stages only optionally involving physiotherapist's modifications bordered with green.

4.4 Mechanical design

4.4.1 Mechanical structure

According to the design intent, the device should enable full mobilisation of the shoulder and elbow joints. Therefore a series kinematic chain parallel to the extremity was used (see figure 3 and corresponding kinematics parameters in Table 3 - joint coordinates [92] are used to describe the system, where φ_i is a rotation of the DOF i regarding the base structure presented in the kinematic chain in figure 3). The wrist joint was fully constrained during the treatment - due to a large number of available rehabilitation devices for this part of the extremity.

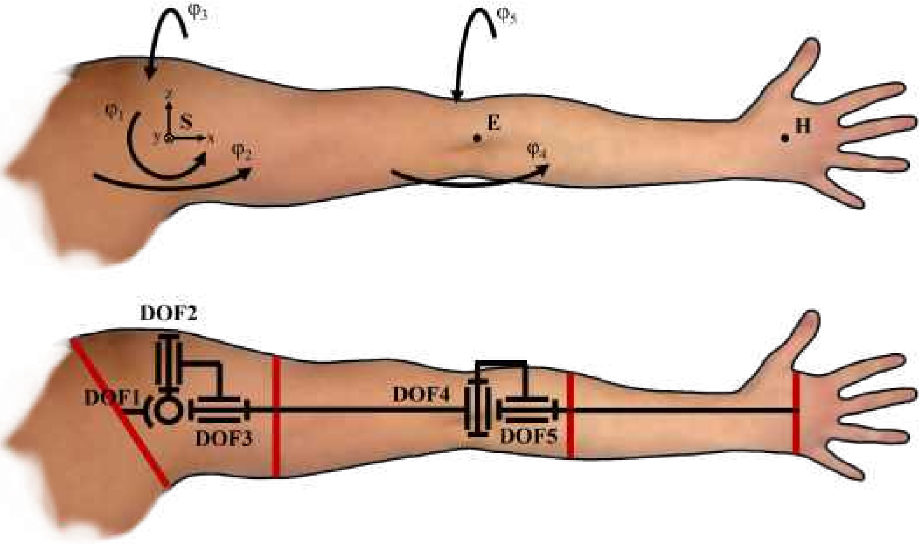


Figure 3: Kinematic models in base configuration (all φ_i equal to 0) of the extremity with the characteristic points (simplified, S - a modelled centre of the shoulder joint, E - a modelled centre of the elbow joint, H - a modelled point of the hand gripping) and exoskeleton (red lines represent points of attachment to the human extremity).

Table 3: Kinematics of the DOFs.

DOF	**Variable**	**Joint**	**Motion**	**Type**	**ROM**
1	φ_1	Shoulder	Flexion (+) / extension (-)	Driven	-140° / 90°
2	φ_2		Abduction (+) / adduction(-)	Driven	-50° / 130°
3	φ_3		External rotation (+) / internal rotation (-)	Free	-50° / 130°
4	φ_4	Elbow	Flexion (+) / extension (-)	Driven	0° / 140°
5	φ_5		Supination (+) / pronation (-)	Free	-80° / 80°

The exoskeleton has five single-DOF joints, three of them (1, 2, and 4) driven and two of them (3 and 5) left free as the plain open sliding bearings. Such a structure is used to guarantee total low weight by reducing the number of motors and not to overconstrain the mobility of the limb at the same time. It consists of twelve main bodies and two additional sliding elements. Its low mass of 8.4 kg is obtainable also thanks to the computationally-optimized design, selected manufacturing method with materials, and lightweight motors. The visual of the exoskeleton is presented in figure 4
The device is attachable to the human extremity by the straps with buckles. They press down the body segments to the soft pads placed within mechanical construction. Thanks to this, the mechanism can be easily unattached in case of emergency. Moreover, soft connection enables minimal compensation of differences between the biomechanical structure of an extremity and the kinematic structure of an exoskeleton (it is modelled as a 5 DOF structure, while human joints are more complex and have the mobility of more DOFs).

For testing purposes, two different mounting plates were designed. One of them allows attachment of the exoskeleton to the patient's back near the shoulder girdle by straps with buckles. The other enables mounting the device to the frame and is designed for research purposes mainly. However, it can also be used for patients with comorbidities, such as problems with the spine, which result in restrictions from using wearable devices supported on the patient's musculoskeletal system. On the other side of the device, there is a handle to grip it by the user. For patients with muscle flaccidity, additional strap attachment is possible.

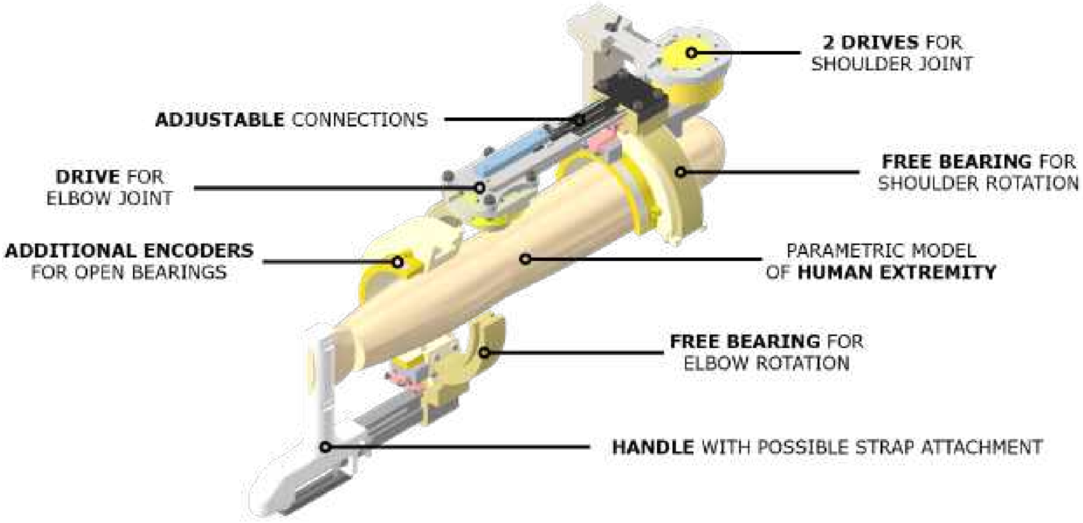


Figure 4: Visual of the designed exoskeleton with the modeled human extremity.

The exoskeleton's dimensions are parametrised in CAD software to remain suitable for the users with upper extremity dimensions between 5th women and 95th men Polish percentile. For this reason, three transverse joints with linear sliding bearings were implemented. Two of them enable regulation of the forearm's and the arm's lengths, while the other enables distancing from the mounting frame. The former ones are additionally equipped with linear potentiometers to measure actual lengths, as they affect the exoskeleton's dynamics (change the moments of inertia and trajectories of the characteristic points). They are presented in figure 5.

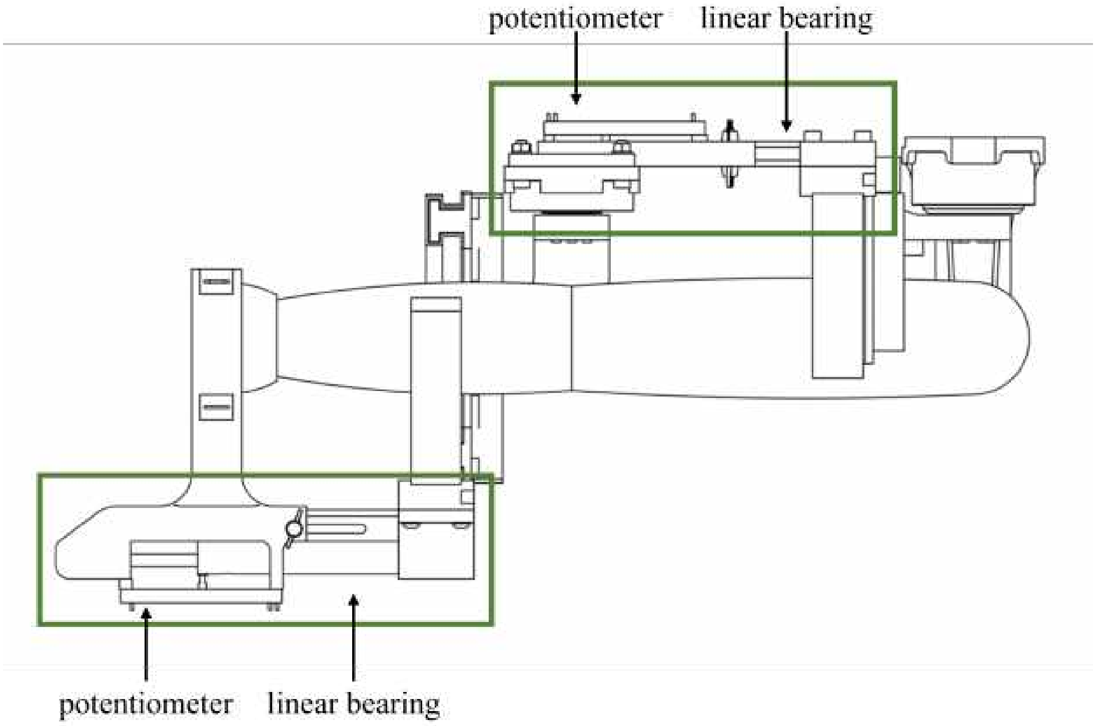


Figure 5: Adjustable transverse joints for setting the forearm's and the arm's lengths presented on a sketch of the exoskeleton.

The free DOFs are designed as plain open sliding bearings which enable shoulder and elbow rotations (see figure 6. As there are no corresponding drives, these DOFs are non-controlled. However, additional magnetic tape encoders by *Lika* enable the observation of rotations with the precision of ±0.1° [2]. These consist of two cooperating main parts each and the inner sliding inserts, which may be easily exchanged while worn. The construction of bearings was numerically optimised and is presented more precisely in the section dedicated to strength validation.

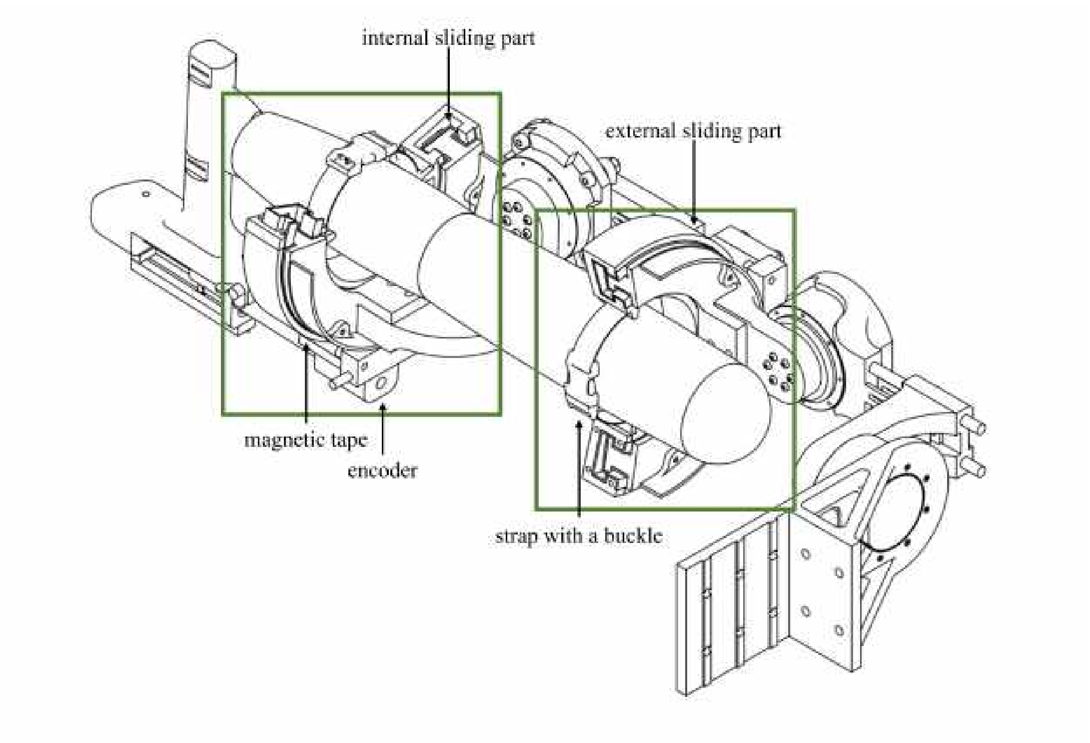


Figure 6: Open sliding bearings presented on a sketch of the exoskeleton.

4.4.2 Drives selection

To select the drives, simplified multibody dynamics (MBD) simulations were run in *Matlab/Simulink* environment (see Figure 7). It consisted of two rigid bodies connected together with the 2-DOFs joint and connected to the ground by a 3-DOFs joint (see Figure 8). Mass parameters of the exoskeleton's and extremity's components corresponding to the rigid bodies were added according to Steiner's theorem. To select the minimum torque required for drives, the kinematic control signal was set to minimally compensate for the gravitational force of the heaviest possible extremity in the straightened configurations (base configuration of the kinematic model from Figure 3 and for an arm parallel to the median plane). The computed values were enlarged with the 1.3 safety factor. Maximum angular velocities needed for the rehabilitation were selected based on the trajectory analyses from the literature sources [123]. Results of the selection are presented in Table 4.

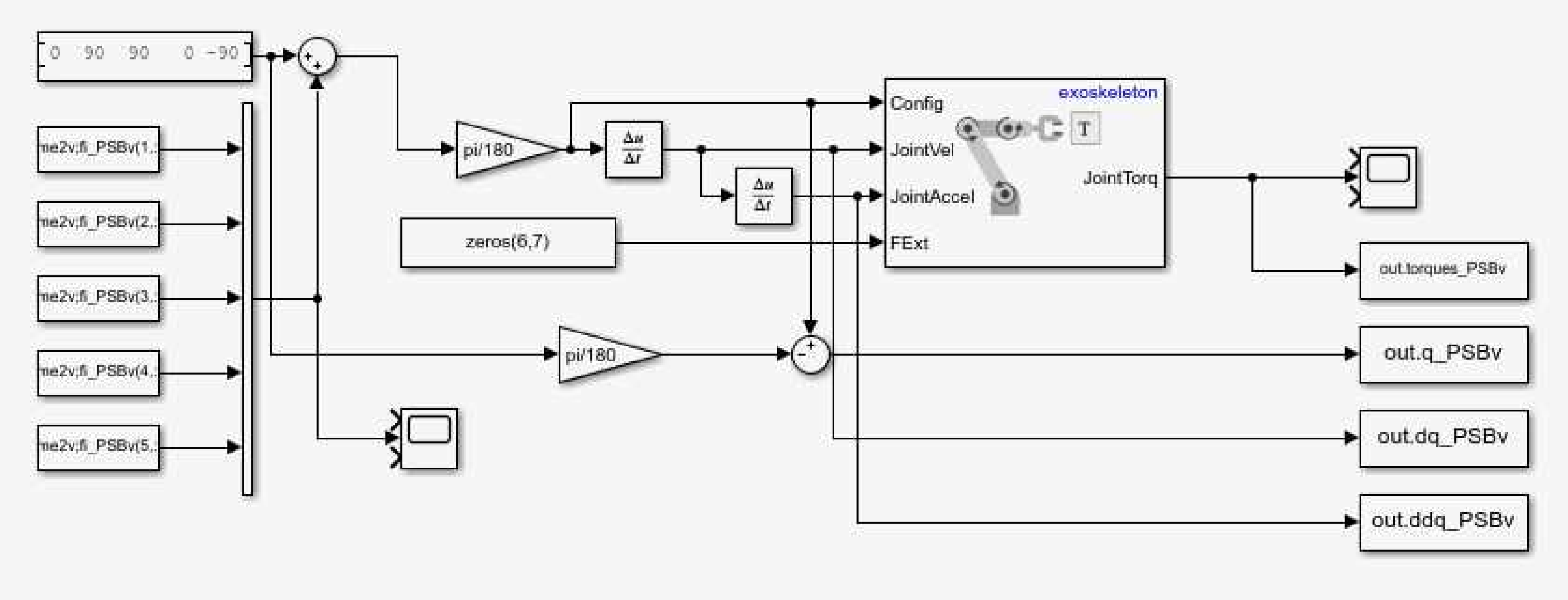


Figure 7: *Matlab*/*Simulink* simplified multibody model used for calculation of driving torques and kinematics of the exoskeleton while following the trajectories.

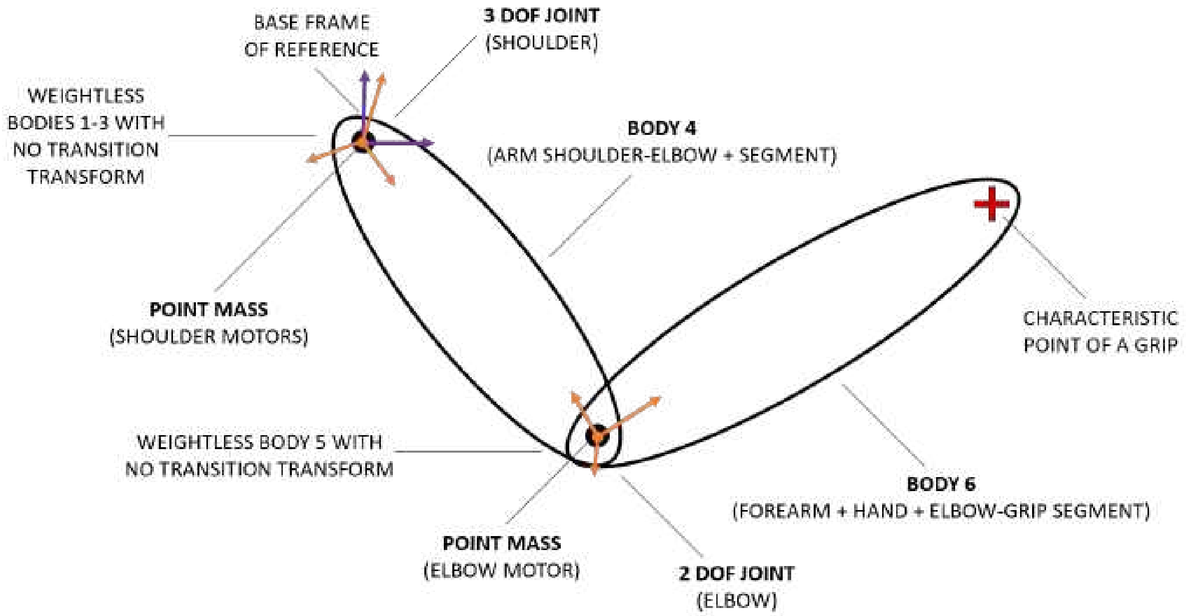


Figure 8: Schematic structure of the simplified MBD model of the exoskeleton with extremity attached.

Table 4: Required torques, angular velocities, and angular accelerations in all DOFs.

DOF	Joint	Type	Torque	Velocity	Acceleration
φ_1	Shoulder	Driven	43.225 Nm	28.65 rpm	23 rad/s^2
φ_2		Driven	43.225 Nm	28.65 rpm	23 rad/s^2
φ_3		Free	-	22.92 rpm	18.3 rad/s^2
φ_4	Elbow	Driven	7.613 Nm	24.83 rpm	19.5 rad/s^2
φ_5		Free	-	11.46 rpm	8.2 rad/s^2

The selected motors are presented in Table 5. As can be observed, the required parameters for the first two DOFs are equal, while the selected models of motors differ. This is due to the failure of *AK80-80* initially selected also for DOF 2 and the withdrawal of this product since. The *AK80-64* fulfils the requirements; thus, it is used to drive the second joint.

The drives were initially only controlled by the original PI controller. Therefore, they could not obtain accuracy better than $\pm 5^o$, which was not sufficient for biomedical applications. To enable easy and accurate control with Python-based programming via CAN protocol, additional controllers from *MAB Robotics* replaced the original ones.

Table 5: Parameters of the selected motors.

DOF	Drive	max. Torque	max. Velocity	Mass
1	T-MOTOR AK 80-80	48 Nm / 144 Nm (peak)	45 rpm / 66 rpm (no load)	780 g
2	T-MOTOR AK 80-64	48 Nm / 120 Nm (peak)	28 rpm / 57 rpm (no load)	850 g
4	T-MOTOR AK 80-9	9 Nm / 18 Nm (peak)	245 rpm / 286 (no load)	485 g

Additionally, the author of this thesis developed a method of automatic motor and power transmission systems selection during his research exchange at the Center for Rehabilitation Robotics of Aalborg University. The designed methodology is presented in an original research paper attached in appendix F [54]. Even though the prototype was built by that time, the approach was applied to the design of the *ExoReha* exoskeleton to analyse further possible constructional modifications. The outcomes of this are presented in an original research paper attached in appendix G[51].

4.4.3 Manufacturing process and materials

The device is designed to 3D print its main parts. Such a choice is aimed at easy modifying and lightweight irregular structure. The first aspect is particularly important for personalised medicine, where health conditions or individual extremity structure can require specific modification of the exoskeleton's components (e.g. to mechanically limit ROMs enabling rising hands above head for people with cardiology issues). As additive manufacturing rises in popularity, the redesigned parts can be quickly manufactured almost everywhere cheap. To guarantee so and minimise the exoskeleton's weight, the considered techniques were limited to simple plastic-based ones.
Initially, the prototype was built in FFF technology from industrial materials - *NanoCarbon (PA12+CF)* and *Iglidur I150*. The first filament was used for the main components, while the sliding bearings were to be manufactured as uniform solids from *Iglidur I150*. However, under maximum considered shear loads, the layers were losing their cohesion due to the orthotropic characteristics of 3D-printed objects. Moreover, the parts from *NanoCarbon (PA12+CF)* were not keeping the intended dimensional accuracy, and the filament itself was very sensitive to humidity. Examples of the mentioned problems are presented in figure 9.

Figure 9: Broken element 3D-printed with FFF technology.

Hence, another method of additive manufacturing was selected. The main components were printed in SLS from *Nylon 12 CF* powder. Moreover, the sliding bearings were divided into main parts and additional sliding inserts. Their main segments were also printed from *Nylon 12 CF* to provide high durability and strength. Change in the technology brought better strength results than previously considered, even though the raw material was nominally less strong. The sliding inserts were printed in FDM from *Diran 410MF07*, as the material was less contracting while printed than *Iglidur I150* and could better fit into the interface gap between the main parts of the bearing. The final printed prototype of the exoskeleton is presented in figures 10 and 11.

The components of the exoskeleton are mostly constrained by screws. However, the threads were not directly drilled into the 3D-printed parts. Most of the connections are realised with the thru-holes with inserted screws and locking nuts. Nevertheless, the most vulnerable ones, in free bearings, were realised with the metal thermo-active thread inserts placed in the technology holes of the main components.

Figure 10: Final prototype of the exoskeleton assembled directly on a user.

Figure 11: Final prototype of the exoskeleton assembled on a test frame.

The assembly drawings of the exoskeleton mechanical part are presented in appendix O with references to the corresponding CAD models of the components.

4.4.4 Strength validation

Key components were validated in terms of their strength with the internal *Autodesk Inventor Stress Analysis* module. The aim of this was to eliminate the risk of decohesion during operation. For this purpose, the components were analysed individually with a fully fixed constraint in the point of interface with the previous component in the kinematic chain and the static load attached to the point of interface with the next element.
The resultant loads were computed with the simplified MBD model in *Adams 2021.1* (see figure 12). The model consists of seven rigid bodies connected with simple 1-DOF revolute joints and a model of the human extremity attached in parallel. The first body was attached by a revolute joint directly to the ground of the model. No additional loads apart from the gravity were considered. The analysis simulated the most dangerous configuration of an exoskeleton. This was assumed as the straightened position with the free bearings rotated maximally and the maximum moments acting in line with maximum angular

velocities and against maximum angular accelerations in DOFs. The loads computed for certain connection points are presented in table 6, where the z axis was assumed as overlaying the rotation axis of a corresponding DOF, and the following parameter state for the following:

- M_x and M_y - bending moments appearing in the centre point of the rotation;
- F_x and F_y - radial forces appearing in the centre point of the rotation;
- F_z - axial force appearing in the centre point of the rotation.

Table 6: Maximum dynamic loads values during extreme motion cases.

	Bending		**Radial**		**Axial**
DOF	**M_x [Nm]**	**M_y [Nm]**	**F_x [N]**	**F_y [N]**	**F_z [N]**
1	0	24.11	-418.29	-5.53	1.69
2	22.427	0	-416.00	5.92	1.37
3	-22.91	43.18	14.39	0.77	-413.80
4	-5.15	0	-157.32	108.12	55.83
5	3.15	-29.45	184.97	55.34	-170.39

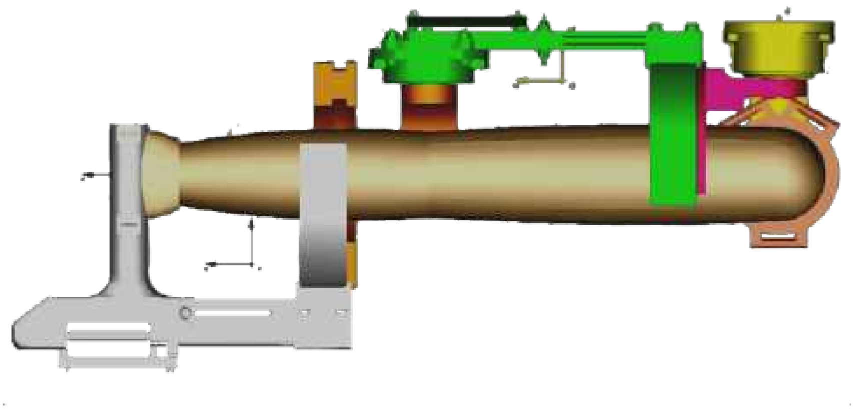


Figure 12: MBD model in *Adams 2021.1* software - colours present different rigid bodies connected one to another.

For the analysis, material models based on the filaments' and powder's suppliers and the literature sources with analogue models were used [132]. The printed structures were modelled as orthotropic with their main directions along the printing or sintering trails. Their mechanical parameters are presented in table 7, where the following parameters are:

- ρ - density;
- E - Young Modulus;
- ν - Poisson's Ratio;
- G - Shear Modulus;
- UTS - Ultimate Tensile Stress.

The parameters were taken directly from their materials datasheets [1],[6] or computed based on parameters from datasheets and proportions applicable to FFF/FDM technology [31]. Such a computation was realised for *Diran 410MF07* shear modulus and Poisson's ratio.

Table 7: Material parameters used in modelling.

	Nylon 12 CF		**Diran 410MF07**	
	Plate directions	**Growth direction**	**Plate directions**	**Growth direction**
ρ [g/cm3]	1.07		0.99	
E [GPa]	3.654	2.461	1.69	1.46
ν	0.3	0.37	0.23	0.3
G [GPa]	1.39	1.15	0.84	0.84
UTS [MPa]	60	51	44.8	-

Additionally, extended strength analysis and the optimisation of the open bearings for previously selected materials were conducted within the additional project realised by a student under the supervision of this dissertation's author. They are described in the paper presented in appendix I.

4.5 Electronic design

The rehabilitation system is equipped with a control cabinet including all the main control electronic and electric components (see figure 13). These include the following, among others:

- *Raspberry Pi 4 B WiFi DualBand Bluetooth 8GB RAM 1,5GHz* microcomputer [7];
- *NUCLEO-H755ZI-Q* board [10] with the *STM32F429ZIT6* microcontroller [11];
- *MAB Robotics CANdle HAT* [3];
- *Secomea SiteManager 1549 (Ethernet, WiFi), 3x DEV, 10 Dev-ag.* remote access industrial router [9];
- *Meanwell UHP-2500-24* AC-DC switching power supply [4];
- *EATON 2P 16A B, AC* circuit breaker;
- 12/24V to 5V 10A converter;
- Switch disconnector.

Figure 13: Control cabinet of the exoskeleton.

A schematic diagram of the electronic components is presented in figure 14. The master device of the control system is a *Raspberry Pi 4* microcomputer. It is connected through the *MAB Robotics CANdle HAT* to the CAN-communicating motors, via UART connection to the NUCLEO-H755ZI-Q board and with the USB and HDMI cables to the tactile operator's panel. It is dedicated to controlling the whole exoskeleton and hosting HMI. Moreover, the microcomputer is connectable to VR for visualisation purposes.

The NUCLEO-H755ZI-Q board is working simultaneously as a tool to serve the analogue devices and a safety system. The former includes magnetic encoders for the free DOFs, potentiometers for measuring dimensional shifts of the adjustable components, and the biosignals tracking system (eight EMG sensors). Furthermore, this enables the integration of additional ICT packages with the system. The latter is limited to the double 5V circuit with the emergency stop in the initial design.

Both the microcomputer and the microcontroller board are connected to the industrial router via an Ethernet connection. This enables safe and stable remote access to the device, as required for the physiotherapist remotely using such a device.

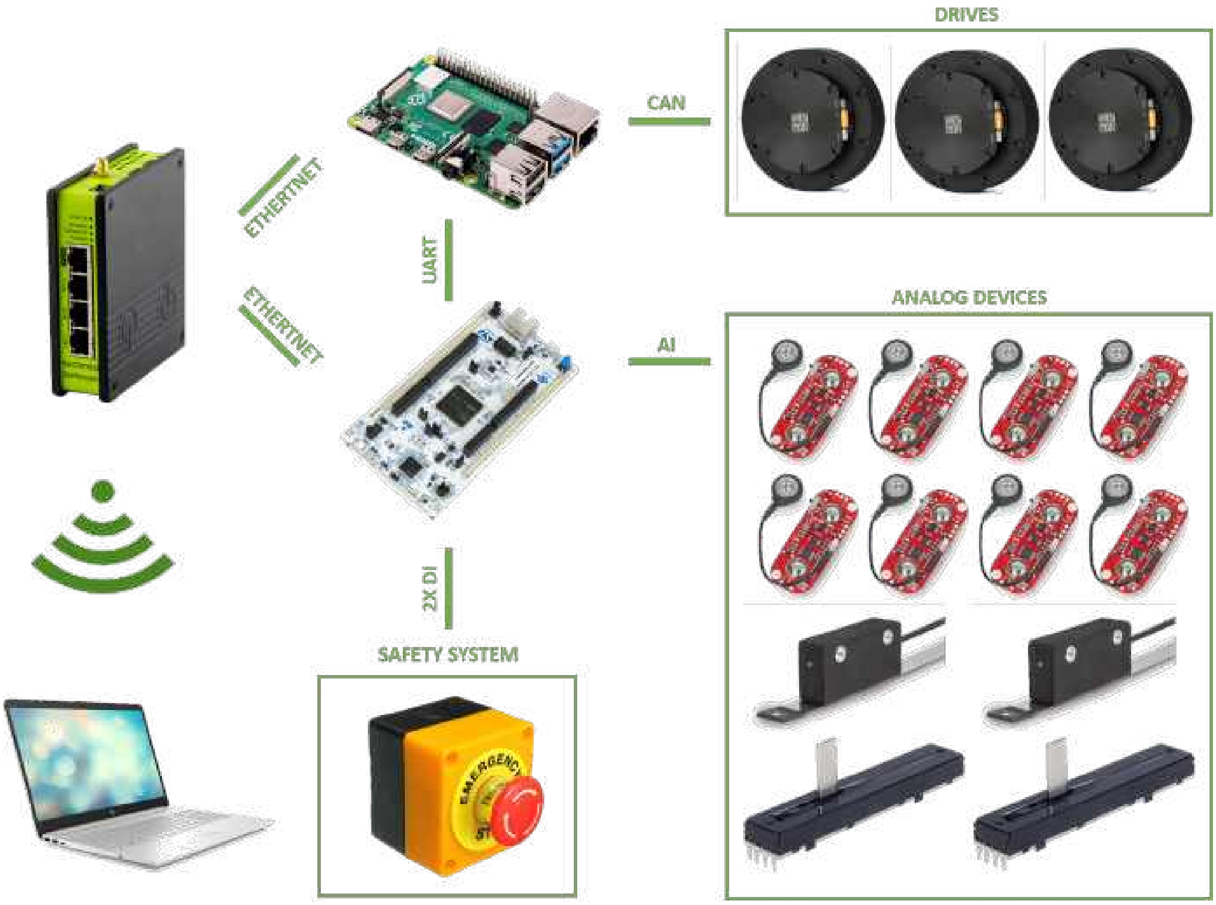


Figure 14: Schematic diagram of the electronic components and communication protocols used in the control system of the exoskeleton (AI - analogue inputs, DI - digital inputs).

4.6 Control system

The basic control system is based on position PID control. The settings for every controller are presented in table 8. The following sections investigate the possibility of implementing more advanced control systems.

Table 8: Settings for PID controllers.

DOF	1	2	4
Drive	T-MOTOR AK 80-80	T-MOTOR AK 80-64	T-MOTOR AK 80-9
$\mathbf{k_P}$	20	20	20
$\mathbf{k_I}$	1	1	0.5
$\mathbf{k_D}$	0.9	0.9	0
Windup	1.5	1.5	15
Max. speed	3 rad/s	3 rad/s	30 rad/s

During position control, the drives follow their desired angular positions (according to the kinematic model from figure 3). These are calculated with the kinematic equations 1 and 2, based on the desired trajectories of the handle characteristic point. The equation 1 represents the trajectory in a Cartesian frame of reference while 2 represents the rotation of the handle in Euler angles. The symbols used in these are as follows:

- $\boldsymbol{r_H^{(i)}}$ - position of the handle characteristic point in *i-th* frame of reference;
- $\boldsymbol{r_E^{(i)}}$ - position of the elbow characteristic point in *i-th* frame of reference;
- $\boldsymbol{R_H^0}$ - handle rotation matrix based on φ_H, ψ_H and θ_H Euler angles;
- $\boldsymbol{R_E^0}$ - elbow rotation matrix based on φ_E, ψ_E and θ_E Euler angles;
- $\boldsymbol{R_j^i}$ - rotation matrix from *i-th* to *j-th* frame of reference;
- l_{SE} - the distance between shoulder and elbow characteristic points;
- l_{EH} - the distance between elbow and handle characteristic points.

$$\boldsymbol{r_H^{(0)}} = \boldsymbol{R_3^0} \cdot \left(\boldsymbol{r_E^{(3)}} + \boldsymbol{R_5^3} \cdot \boldsymbol{r_H^{(5)}} \right) = \boldsymbol{R_y}(\varphi_1) \cdot \boldsymbol{R_z}(\varphi_2) \cdot \boldsymbol{R_x}(\varphi_3) \left(\boldsymbol{r_E^{(3)}} + \boldsymbol{R_z}(\varphi_4) \cdot \boldsymbol{R_x}(\varphi_5) \cdot \boldsymbol{r_H^{(5)}} \right) \tag{1}$$

$$\boldsymbol{R_H^0} = \boldsymbol{R_5^0} = \boldsymbol{R_y}(\varphi_1) \cdot \boldsymbol{R_z}(\varphi_2) \cdot \boldsymbol{R_x}(\varphi_3) \cdot \boldsymbol{R_z}(\varphi_4) \cdot \boldsymbol{R_x}(\varphi_5) \tag{2}$$

For calculations of particular joint variables, extended equations 3-4 can be applied.

$$\boldsymbol{r_H^{(0)}} = \begin{bmatrix} \cos\varphi_1 \cdot \cos\varphi_2 \cdot (l_{SE} + l_{EH} \cdot \cos\varphi_4) - \sin\varphi_4 \cdot (sin\varphi_1 \cdot \cos\varphi_3 - \cos\varphi_1 \cdot \sin\varphi_2 \cdot \sin\varphi_3) \cdot l_{EH} \\ \sin\varphi_1 \cdot \cos\varphi_2 \cdot (l_{SE} + l_{EH} \cdot \cos\varphi_4) + \sin\varphi_4 \cdot (cos\varphi_1 \cdot \cos\varphi_3 + \sin\varphi_1 \cdot \sin\varphi_2 \cdot \sin\varphi_3) \cdot l_{EH} \\ \cos\varphi_2 \cdot \sin\varphi_3 \cdot \sin\varphi_4 \cdot l_{EH} - \sin\varphi_2 \cdot (l_{SE} + l_{EH} \cdot \cos\varphi_4) \end{bmatrix} \tag{3}$$

$$\boldsymbol{R_H^0} = \begin{bmatrix} \cos\varphi_H \cdot \cos\psi_H - \sin\varphi_H \cdot \sin\psi_H \cdot \cos\theta_H & \sin\varphi_H \cdot \cos\psi_H + \cos\varphi_H \cdot \sin\psi_H \cdot \cos\theta_H & \sin\varphi_H \cdot \sin\psi_H \\ -\cos\varphi_H \cdot \sin\psi_H - \sin\varphi_H \cdot \cos\psi_H \cdot \cos\theta_H & -\sin\varphi_H \cdot \sin\psi_H + \cos\varphi_H \cdot \cos\psi_H \cdot \cos\theta_H & \cos\varphi_H \cdot \sin\psi_H \\ \sin\varphi_H \cdot \sin\theta_H & -\cos\varphi_H \cdot \sin\theta_H & \cos\psi_H \end{bmatrix} \tag{4}$$

Computation of the system's inverse kinematics in *Simulink* environment requires a *rigidBodyTree* model based on the Denavit-Hartenberg (DH) parameters. These, for the final prototype structure, are presented in table 9. The additional parameter d_S is an adjustable offset of the second drive's axis from the back mounting plate, either attached to the shoulder or the frame.

Table 9: Denavit–Hartenberg parameters of the exoskeleton.

DOF	$\boldsymbol{\alpha_i}$	$\boldsymbol{a_i}$	$\boldsymbol{d_i}$	$\boldsymbol{\theta_i}$
1	-90^o	0	d_S	$\varphi_1 + 90^o$
2	90^o	0	0	$\varphi_2 + 90^o$
3	-90^o	0	l_{SE}	φ_3
4	-90^o	0	0	φ_4
5	90^o	0	l_{EH}	φ_5

As the exoskeleton enables full mobilisation of shoulder and elbow joints, the kinematic chain formulas 5 - 7 can also be used to control elbow position. Even though DOFs 1-3 work as a sphere joint, their correlated joint variables are not identical to Euler's angles for the elbow due to the different order of joints. For this reason, equations 6 and 8 can be used to compute the desired orientations.

$$\boldsymbol{r_E^{(0)}} = \boldsymbol{R_3^0} \cdot \boldsymbol{r_E^{(3)}} = \boldsymbol{R_y}(\varphi_1) \cdot \boldsymbol{R_z}(\varphi_2) \cdot \boldsymbol{R_x}(\varphi_3) \cdot \boldsymbol{r_E^{(3)}} \tag{5}$$

$$\boldsymbol{R_E^0} = \boldsymbol{R_3^0} = \boldsymbol{R_y}(\varphi_1) \cdot \boldsymbol{R_z}(\varphi_2) \cdot \boldsymbol{R_x}(\varphi_3) \cdot \tag{6}$$

$$\boldsymbol{r_E^{(0)}} = \begin{bmatrix} \varphi_1 \cdot \cos\varphi_2 \cdot l_{SE} \\ \cos\varphi_2 \cdot \sin\varphi_1 \cdot l_{SE} \\ -\sin\varphi_2 \cdot l_{SE} \end{bmatrix} \tag{7}$$

$$\boldsymbol{R_E^0} = \begin{bmatrix} \cos\varphi_E \cdot \cos\psi_E - \sin\varphi_E \cdot \sin\psi_E \cdot \cos\theta_E & \sin\varphi_E \cdot \cos\psi_E + \cos\varphi_E \sin\psi_E \cdot \cos\theta_E & \sin\varphi_E \cdot \sin\psi_E \\ -\cos\varphi_E \cdot \sin\psi_E - \sin\varphi_E \cdot \cos\psi_E \cdot \cos\theta_E & -\sin\varphi_E \cdot \sin\psi_E + \cos\varphi_E \cdot \cos\psi_E \cdot \cos\theta_E & \cos\varphi_E \cdot \sin\psi_E \\ \sin\varphi_E \cdot \sin\theta_E & -\cos\varphi_E \cdot \sin\theta_E & \cos\psi_E \end{bmatrix} \tag{8}$$

More advanced control systems were analysed at the next stages of the presented research on the applicability of ICTs. The results are presented in the following sections. For physiotherapeutic purposes, not only classic control approaches based on following the trajectories computed with the kinematics equations and predicting the behaviour of the system with the MBD model should be used. Within the therapy, an almost real-time optimisation problem has to be solved. The function to be minimised has to comprise the conventional equation as for the follow-up control, based on the kinematic inaccuracies, but also the component for unanatomical motion patterns (e.g. patients' compensations due to their lack of mobility in certain joints) and non-functional motions (e.g. too large hand tilts for actions such as drinking). The concept of the optimisation problem is described in the paper presented in appendix C [49].

4.7 Human-machine interface

The built prototype was used mainly for the research on impacting patients' musculoskeletal systems by the use of ICTs. Therefore, either none or ICT-based human-machine interfaces (HMI) were used. The latter are presented in the following sections.
However, the end product should have a dedicated interface for the device's operator. During the development works, a concept of such was designed. It is designed to be used with the tactile operator panel connected directly to the *Raspberry Pi* microcomputer (its prototype is presented in figure 15). The HMI enables initial preparation for the treatment, selecting workout routines, adding new exercises, and using the automatic treatment. During the exercises, the real and obtained positions should be visualised. However, it can be challenging due to the limited immersion of the small flat screen-based presentation.

Figure 15: A prototype of the tactile operator panel.

4.8 Rehabilitation routine

The considered rehabilitation routine has to correspond to the needs of task-oriented kinesiotherapy. Hence, the selected motion trajectories have to reflect daily-life activities. According to the in-depth interviews with potential users conducted at Aalborg University, the following types of activities are the most significant for impaired people [136]:

- Eating (snacking - using assistance for eating a whole meal is less hindering than asking for help in grabbing every piece of food);
- Drinking (sipping - analogically to eating);
- Scratching (particularly facial region);

- Turning over pages of newspapers and books;
- Personal grooming.

Based on these, these trajectories were registered. Additionally, the database was also enhanced by the activities significant for patients with less severe impairment, among others:

- Using a computer with a computer mouse or a typing keyboard; particularly problematic for patients with wrist extension disabilities [74];
- Dressing; particularly problematic for people with reaching impairment and fine motor control [74][48];
- Writing; problematic for people with fine motor control [74];
- Preparing food; problematic for people with bimanual coordination [48];
- Carrying shopping bags; problematic for people with bimanual coordination [48];
- Work-related operation of the machinery or driving a car with a steering wheel [74].

Moreover, simple exercises for joint mobilisation were added to the set.

The trajectories obtained in the time series for the characteristic gripping point were processed with the inverse kinematics model in *Simulink*. Thanks to these, the trajectories for the internal joint variables were computed. These are used at the further stages of the research to define the desired rotations of the rehabilitation exoskeleton's motors.

4.9 Summary

This section describes the complete process of the exoskeleton design and its final outcomes. The former included mechanical design with simulations, subcomponents selection, material selection, manufacturing tests and final assembly, electronic design with the manufacturing of the control cabinet, integration of the system and control system design, UI conceptual design, and treatment planning. These formed the physiotherapy system based on the exoskeleton with the programme adjusted to the task-oriented therapy based on the ADLs. The outcome of the works were used for the final experimental trials as the device supporting kinesiotherapy.

5 Implementation of selected ICTs

5.1 Introduction

This section describes ICTs developed and tested within the investigation. These include artificial neural networks for control algorithms, an EMG tracking system, VR visual for the patient, and the digital twin for remote control of the exoskeleton. The section includes only application, equipment, and methodology descriptions. The test procedures used for assessment of the quality of the selected ICTs are elaborated on in the following section.

5.2 Neural networks for motion predicting

The nonlinear autoregressive exogenous neural networks (NARX) give an opportunity to predict the dynamics of the exoskeleton more accurately without the precise knowledge of the mass distribution in a patient's extremities. As the exoskeleton has two free DOFs, such a process can be more difficult. For this reason, the concept of using NARX in predictive control was evaluated based on the MBD simulation. The results of the experiment were described in a scientific paper presented in the appendix D[50]. These prove that the proposed methodology can be used to estimate future configurations of the rehabilitation exoskeleton with the extremity and control the support more accurately or prevent potential hazards. Additionally, the tests of predicting user intentions for active control of the exoskeleton without AI were described in the scientific paper attached in the appendix L [53].

5.3 EMG tracking

Tracking the electrical activity of the user's muscles was selected as one of the methods to validate the treatment efficacy. Therefore, a system enabling the registration of such biosignals was designed. It is dedicated to tracking the muscular groups, fully mobilising shoulder and elbow joints. Hence, eight of them were selected [150][30][16], and the system consisting of eight EMG *MyoWare Muscle Sensors* with the dedicated *Cable Shields* was designed (see figure 16). The placement of the desired end and middle electrodes is presented for every channel in figure 17. The reference electrodes are each attached to the lateral facets with the thinnest amount of fat layer around the elbow and the wrist.

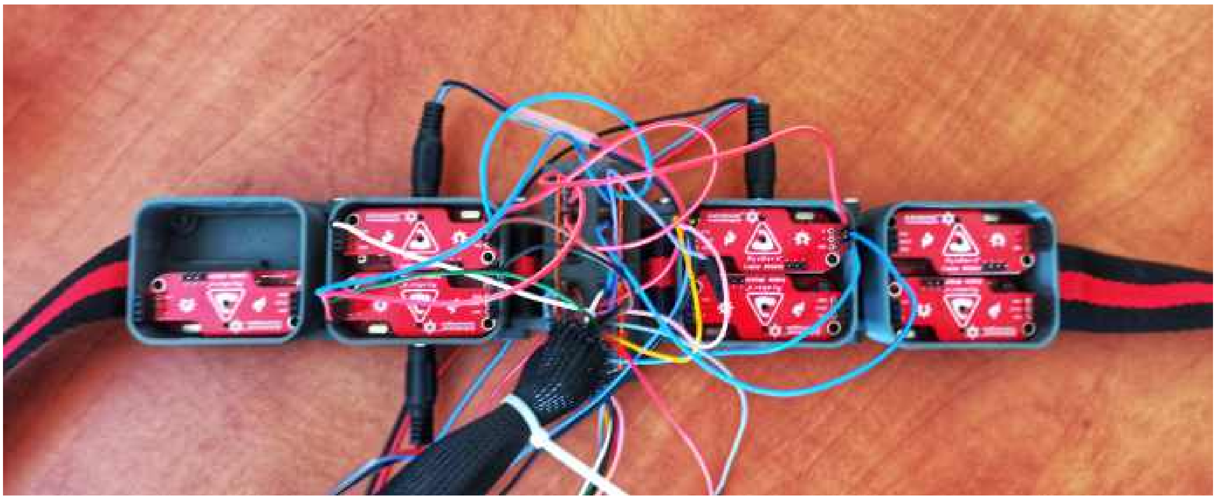


Figure 16: An 8-channel EMG belt.

Figure 17: Placement of the electrodes; channel 1 - deltoid muscle (middle), channel 2 - deltoid muscle (rear), channel 3 - pectoralis major, channel 4 - teres major muscle, channel 5 - latissimus dorsi muscle, channel 6 - biceps brachii, channel 7 - triceps brachii, channel 8 - brachioradialis.

The EMG belt signal outputs are connected with the analogue signal inputs of the microcontroller (*STM32F429ZIT6*). The setup enables registration of both post-processed signals (SIG) and raw electric activity (RAW). The microcontroller projects these into float variables of a value 0-4095. Hence, the shift of the RAW signals is required. This is realised by subtracting half of the measurement range, 2048, from the registered value.

The performance of the system was validated with the involvement of this thesis author. It was confirmed that the sensors used for the setup need precise calibration prior to experiments. The differences between the activation of one person's certain muscular groups are enough to disable the use of the same adjustments for all of them. If omitted, the signals can be too weak to be registered or exceed the measuring range. Moreover, the individual differences in the patient's anatomy (e.g. fat layer thickness) are even more significant. For these reasons, calibration with the potentiometers is needed at the beginning of the experimental phase every time. The exemplary result of the activity registered for the muscular groups mobilising elbow joint is presented in figure 18. As may be observed, the RAW signals have a lower risk of exceeding the registrable range. Hence, they are primarily used for the analysis of the patient's performance. On the contrary, the SIG signals can be obtained with a lower delay than fully processed RAW signals. Therefore, they are superior in close to real-time applications.

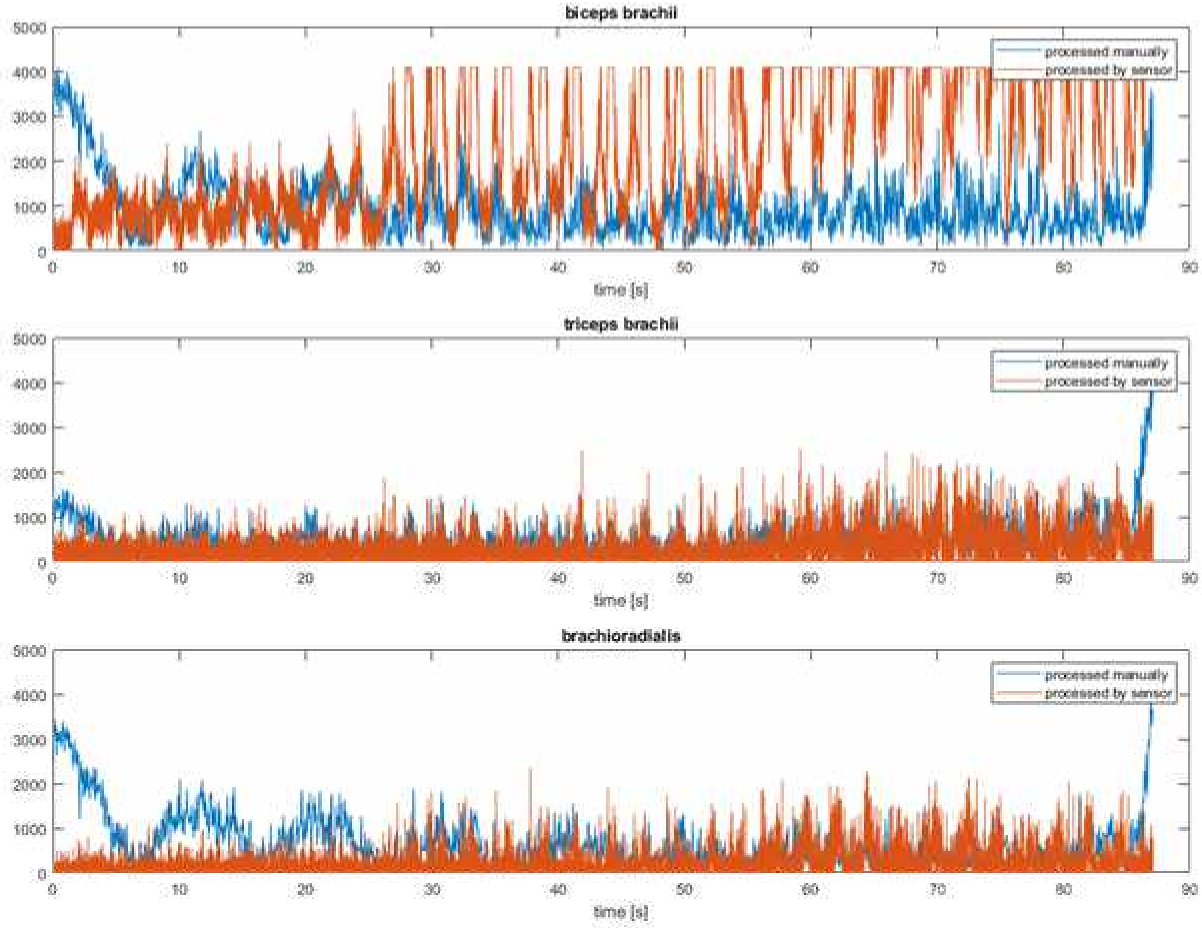


Figure 18: Example of signals registered for three different muscle groups mobilising elbow joint during three sessions of elbow flexion - without additional load, with 2.5 kg added and with 5 kg added; The signal for biceps with additional load exceeds the upper limit of the registrable range while processed automatically by the sensor.

Within the project, a set of wireless EMG sensors was purchased. It consisted of eight *ANR M40* muscle sensors and two *ANR R24* receivers. It was used alternatively for the experiments, as the noise from the cables was eliminated.

The registered signals were initially filtered via a second-order highpass filter with a 50 Hz cut-off frequency to eliminate the noise from cables and motion artefacts (30 Hz cut-off frequency for the wireless sensors) and a second-order lowpass filter with a 500 Hz cut-off frequency to limit analysis only to the EMG frequency range [26][144]. Then, the 49-51 Hz band-stop filter was applied to eliminate power line contamination [26]. The received data were amplified and rectified.

Within the experiments, the patient is constantly attached to the EMG tracking system.

The electrodes are placed as visualised in figure 17. All the signals measured are used to compare muscle activity within different variants of the treatment for an individual patient. Due to individual differences, these cannot be used to compare muscular activity between different people.

5.4 VR visualisation

A user interface for kinesiotherapy with an active exoskeleton should enable an understanding of the intended motion. Therefore, the desired configuration has to be displayed in regard to the actual position of the extremity. However, a conventional approach to such visualisation can be less understandable for a user than the one with selected ICTs. The conducted research aims to compare the accuracy achieved within robot-aided therapy while using three variants of user interfaces (UI) that are different in terms of complexity. These are:

1. 2D user interface with sliders (visual scales) representing five degrees of freedom one below another (see figure 19);
2. 3D user interface with two semi-transparent models of humans representing real-life and the desired positions of the extremity, as seen in the mirror (see figure 20);
3. 3D user interface in VR with two semi-transparent models of humans representing real-life and the desired positions of the extremity, as seen from the first person perspective (see figure 21);

All the user interfaces were developed in the *Unity 2020.3.34f1* environment with the additional *SteamVR Plugin 2.8.0* for the VR-based one. Their functionalities are described more precisely one by one in the following paragraphs.

The basic UI visualised in figure 19 is based on five sliders representing rotations in one degree of freedom each. Their full length corresponds to the range of -180° to 180°. However, the rotations, non-achievable due to the anatomy or limitations of individuals, are excluded from the exercises. These ranges are visualised with the grey bars on the sliders. Real-life and desired positions are represented by two indicators moving along the sliders. The aim of a patient is to move their extremity to follow the indicators corresponding to the desired position by the ones corresponding to the real-life position. The base configuration of the extremity with zero rotations is represented with the red vertical line. Additionally, the real-life and the desired angles of rotations are presented on the right side of the sliders. The user interface can be displayed on computer screens or mobile devices. For the experimental trials, a 24" screen was used.

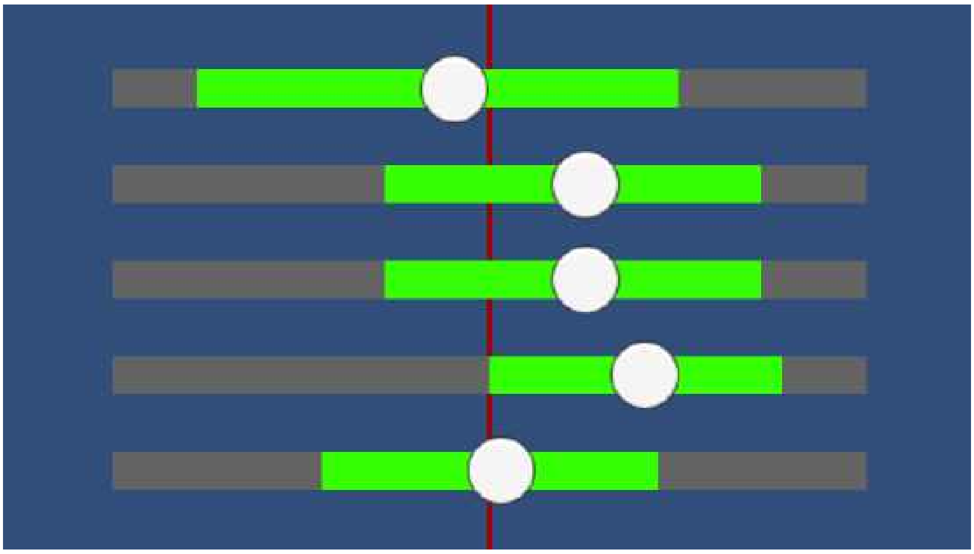


Figure 19: User interface with 2D sliders for every degree of freedom.

The UIs with the 3D human models were developed in two versions - for regular 2D displays (see figure 20) and for VR (see figure 21). Both of these are based on the same project containing two rigid multibody models of a full-body human from *3D Character Dummy* package by *Kevin Iglesias* overlaying one another. Their shoulder and elbow joints are animated based on the five rotations corresponding to the kinematic model from figure 3. This is realised by updating the rotations of the arm and forearm components in the model structure. The rest of the models' bodies remain still.
One of the models, in orange colour, represents the real-life configuration of the extremity. The other, semitransparent in green colour, is a visual of the desired position. This should enable a more natural perception of the therapy compared to the 2D UI. The two developed versions of the interface differ in terms of the defined cameras. For the standard 2D displays, a static camera is placed in front of the models. It represents the scene as in figure 20. The VR camera is interactive, and it is placed in the centre of the models' heads. Therefore, it enables immersive observation of the scene from different perspectives, as in figure 21. For the experimental trials, the UIs are displayed in a 24" screen and *HTC VIVE Cosmos*, respectively.

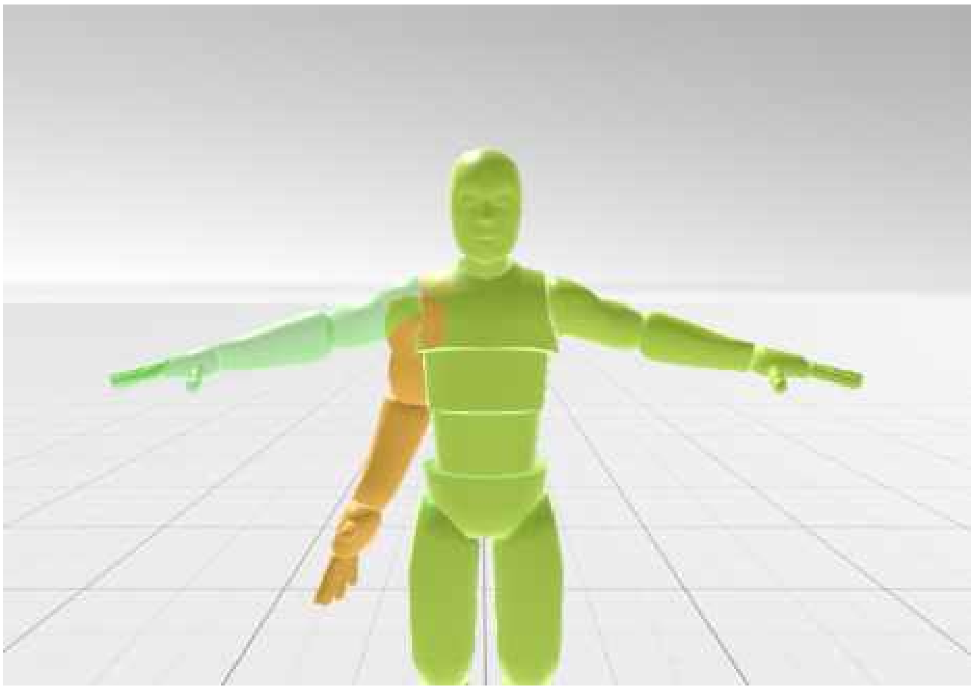


Figure 20: User interface with the 3D models of humans representing real-life and the desired positions

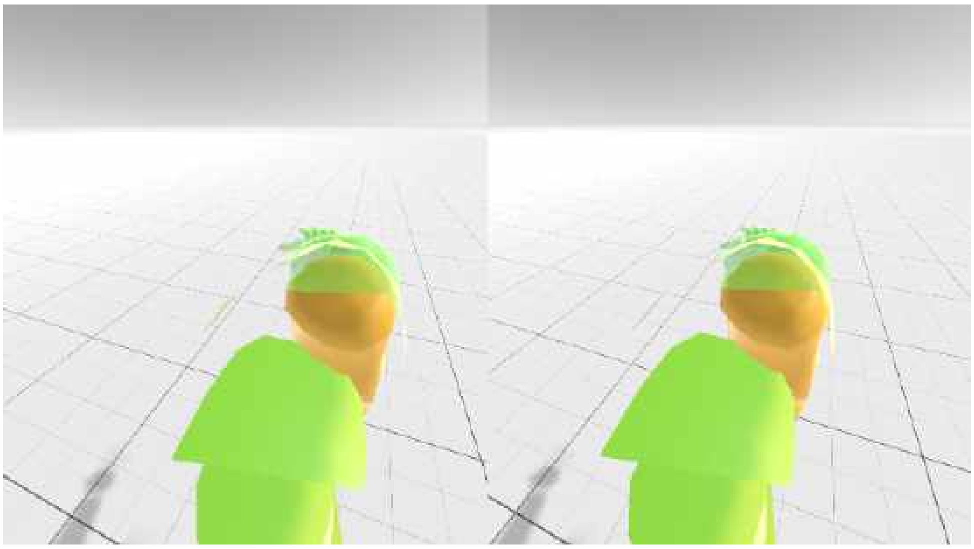


Figure 21: User interface in VR (the same interface as in figure 20) presented from the first person view, divided for the image for left and right eye separately.

5.5 Digital twin

To enable almost real-time monitoring of the therapy performance and remote control over particular DOFs, a digital twin of the exoskeleton and an extremity of a patient was designed in *ROS 2* environment. It consisted of the multibody model with seven rigid bodies for the device and two bodies for the extremity. The set communication enables remote access via the industrial *Secomea SiteManager 1549* router to visualise the current

configuration in the graphical user interface (GUI) based on the Gazebo package and to control the three motors' positions with the sliders. The structure and application of the digital twin are described in a scientific paper presented in appendix H [52].
All the activities undertaken to develop and integrate the digital twin were conducted within the additional project realised by a student under the supervision of this dissertation's author.

5.6 Summary

The section described developed ICTs, including artificial neural networks for control algorithms, an EMG tracking system, VR visual for the patient, and the digital twin for remote control of the exoskeleton. The following experimental phase includes two main stages. First, it is dedicated to testing the impact of the selected visual method to verify the effectiveness of using a VR-based environment. Then, it enables assessing the quality of the robot-aided task-oriented physiotherapy compared with the conventional treatment with the physiotherapist. Assessment of this is based on the sEMG (surface EMG) measurements for the selected muscular groups.

6 Validation of performance

6.1 Introduction

This section is dedicated to the presentation of the investigation experimental phase. The trials are divided into two main parts - assessment of the impact of the visual method on the accuracy of trajectory following and validation of muscular activity during exoskeleton-aided physiotherapy compared to the conventional therapy with the specialist onsite. The section includes an accurate setup and procedure description, the results of the experiment, and a discussion on outcomes. These are accompanied by an analysis of the control system quality and the individual perception of the participants, as well as additional technological and UX aspects.

6.2 Experimental setup

Experimental trials were conducted according to the experimental routine in a continuous series for one participant. Therefore, within a series, the experimental setup was changed. In general, the following pieces of equipment were be involved:

1. *ExoReha* active exoskeleton with three driven and two free joints;
2. Passive exoskeleton with a kinematic structure corresponding to the *ExoReha* exoskeleton (see figure 22 and the paper in appendix M [103]), with five 14-bit encoders at joints registering joint variables within motion via the *STM32L476RGT6* microcontroller board separated from the *ExoReha* exoskeleton;
3. EMG tracking 8-channel system with *MyoWare Muscle Sensors* registering raw and processed signals simultaneously via the *STM32L476RGT6* microcontroller board integrated with the *ExoReha* exoskeleton;
4. *HTC VICE Cosmos* VR goggles connected to the external computer, exchanging data with the *Raspberry Pi* microcomputer remotely via *ROS* system and with additional *STM32L476RGT6* microcontroller board via *USB* cable connection;
5. 24" screen connected to the external computer, exchanging data with the *Raspberry Pi* microcomputer remotely via *ROS* protocol and with additional *STM32L476RGT6* microcontroller board via *USB* cable connection.

Figure 22: Presentation of an exemplary experimental setup with a passive exoskeleton (2) and the VR goggles (4) used for experimental trial 4 from the experimental routine A.

6.3 Experimental routine

The main experimental phase included two main investigation phases - analysing the impact of the visualisation methods on motion accuracy and analysing the effects of robotised treatment on muscular electrical activity compared with conventional treatment. Due to the differences in the required equipment and the long process of exchanging these, the experiments were divided into two. Their experimental routines are presented below.

Experimental routine A:

1. Pre-experimental interview with a participant regarding their health conditions;
2. Attachment of the lightweight measuring device to the participant's extremity with the straps and soft pads;
3. **Experimental trial 1:** Manual leading the extremity along the predefined trajectories by a physiotherapist while registering the joint rotations in time series;
4. **Experimental trial 2:** Following the trajectories visualised at the screen with the bars dedicated to single rotations with the extremity while registering the joint rotations in time series;
5. **Experimental trial 3:** Following the trajectories visualised at the screen by the MBD model with the extremity while registering the joint rotations in time series;
6. Equipping the participant with a VR headset;
7. **Experimental trial 4:** Following the trajectories visualised in VR with the MBD

model with the extremity while registering the joint rotations in time series;

8. Unequipping the participant with the VR headset;
9. Disattachment of the measuring device;
10. Control of participant's side effects;
11. Survey on participant's perception of the VR-based treatment, including side effects.

Experimental routine B:

1. Attachment of the exoskeleton to the participant's extremity with the straps and soft pads;
2. Pre-experimental interview with a participant regarding their health conditions;
3. Manual measurements of the participant's ROM, dimensions of a shoulder-elbow and elbow-gripping point distances, and weight considering their gender;
4. Attachment of the EMG measuring sets to the eight muscular groups;
5. **Experimental trial 5:** Manual leading the extremity along the predefined trajectories by a physiotherapist while registering the joint rotations by the exoskeleton and EMG signals in time series;
6. **Experimental trial 6:** Following the trajectories registered during trial 5, visualised at the screen by the MBD model with the extremity while registering the joint rotations and EMG signals in time series - with the full support of the exoskeleton;
7. Disattachment of the exoskeleton from the participant's extremity;
8. Disttachment of the EMG measuring sets to the eight muscular groups;
9. Control of participant's side effects;
10. Manual measurements of the participant's ROM;
11. Survey on participant's perception of the robot-aided exercises compared to the manual mobilisation of joints, including side effects.

All the experiments were conducted under the approval of the ethical committee for research involving humans - see appendix S.

The experiment based on the experimental routine A is described in-depth in the attached research paper (see the appendix N [55]). This includes description of the participant group, measurement equipment, detailed experimental procedure, and results with corresponding discussion.

The experiment based on the experimental routine B is the main investigation within this thesis. Ten healthy participants (eight male and two female) took place in the measurements. They all volunteered in the trials and signed the informed consent to participate in the study. Their registered data was anonymized and then post-processed according to the presented routines. However, the average parameters of the participants are presented in the table 10.

As can be observed, the group consisted of young people of different heights and weights, falling between the 5$^{\text{th}}$ female and 95$^{\text{th}}$ male percentile of the Polish population. To enable potential multibody visualisation of their movements for the validation process, their upper extremity segments were measured along their long axes. Moreover, their ranges of motion were assessed for shoulder, elbow and wrist joints, even though the last of these was not activated within the tests.

During the pre-experimental measurements, it turned out that two of the participants had outstanding limitations in ranges of shoulder adduction/abduction and shoulder rotation. However, the test movements were designed in a way that did not require ranges exceeding the measured for them. Therefore, the participants were not excluded from the investigation.

Table 10: Participants parameters measured prior to the experiments.

Value	**Unit**	**Average ROM**	**Deviation**
Age	years	21.8	-2.8/+7.2
Height	cm	179.5	-14.5/+11.5
Mass	kg	80.2	-25.2/+34.8
Shoulder-elbow distance	mm	314.7	-38.7/+20.3
Elbow-wrist distance	mm	269.7	-20.7/+20.3
Wrist-grip distance	mm	81.8	-22.8/+12.2
Shoulder flexion/extension	deg	192.1	-20.1/+23.9
Shoulder adduction/abduction	deg	165.7	-38.7/+14.3
Shoulder internal/external rotation	deg	141.3	-47.3/+20.7
Elbow flexion/extension	deg	139.8	-9.8/+10.2
Pronation/supination	deg	164.7	-14.7/+25.3
Wrist flexion/extension	deg	150.8	-29.8/+34.2
Wrist adduction/abduction	deg	53.4	-15.4/+18.6

6.4 Visual method impact on accuracy

Within experimental routine A, the correlation between the obtained accuracy of the realised trajectory and the method of visualisation (for GUI) was analysed. A description of the experimental phase and the obtained results were presented in the attached research paper (see the appendix N) [55]). In general, the accuracies obtained for the 2D visual methods raised significantly with changing slider bars into phantom representation. On the contrary, the possibility of observing motion naturally from different angles in VR did not contribute to further increases in this visual approach.

6.5 Muscle activity during treatment

The muscular activity of the participants was compared for the manual therapy and the robot-aided therapy performed along the same trajectories according to experimental routine B (experimental trials 5 and 6). The same participant was initially undergoing manual therapy guided by a physiotherapist and representing the following ADLs - consequently three times every motion type one after another:

- Drinking (sipping);
- Eating (snacking);
- Scratching ribs;
- Brushing hair;
- Reaching an object from a drawer;
- Pressing a button.

All of these were performed with the ExoReha exoskeleton attached. The device was recording the trajectory and then, inserting the angles into the database with the database timestamps during the whole trial. However, all the drives were released. Simultaneously, the wireless EMG recording system was inserting the EMG measurements into the same database with the timestamps. Thanks to this process, the measurements can be synchronised. All the registered analogue electrical signals were mapped into the range of 0-100 regarding the maximum contraction of individuals.

Then, the participant performed the same motions with the full support of the exoskeleton along the registered trajectories while instructed to act in line with the drives' forces. The muscular groups were analysed in correspondence to the motion in every DOF. The muscular groups were considered antagonists or agonists based on the extremity configuration and the velocity in every joint. Hence, their activation levels were expected to be different. Their average and maximum constant (differing less than 10% within a single contraction) activation were compared between the trials with the physiotherapist support and the exoskeleton support. Moreover, the total time of the correct activation for each muscular group within the experiments was also analysed for the same trials. The comparison was conducted for every participant individually, while the ratio outcomes were then analysed for the whole group.

The experimental setup used for this phase is presented in figure 23. The exoskeleton mounted at the test frame was attached to the participants within their arm and forearm region by straps. Figure 23 represents the recording of motions by a physiotherapist and the monitoring of the recordings by an additional system operator. The participant has eight wireless EMG sensors attached. They are additionally stuck with the medical tape to prevent them from moving relative to the muscles.

Figure 23: Dependance of the muscular contraction levels on the direction of motion in the corresponding DOF and configuration of the extremity regarding gravitational acceleration vector.

The muscular groups are considered agonists or antagonists based on the activity they affect upon a joint. The former contracts, while the other relaxes (see figure 24). The list of the measured muscular groups considered agonists or antagonists of activated DOFs (within their positive motion) is presented in table 11.

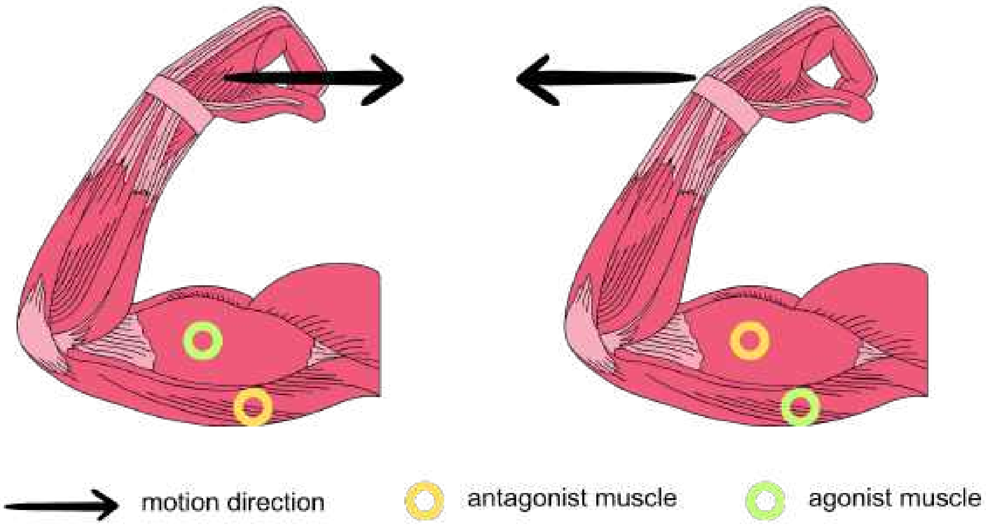


Figure 24: Example of agonist and antagonist muscles dependent on the direction of motion in the certain DOF.

Table 11: List of the measured muscular groups (enumeration as channels in figure 17) considered agonists or antagonists of activated DOFs (within their positive motion).

Muscular group	**Function regarding DOFs**
1	DOF1 (+) agonist
2	DOF1 (+) agonist
3	DOF2 (+) agonist
4	DOF2 (+) antagonist
5	DOF1 (+) antagonist
6	DOF4 (+) agonist
7	DOF4 (+) antagonist
8	DOF4 (+) agonist

The contraction level in the muscular groups also depends on the extremity configuration in the gravitation field (see figure 25). The motions in the direction of the gravitational acceleration (e.g. during eccentric exercises; cases b, c and e in figure 25) result in possible low activations of agonist and antagonist groups with the magnitude dependent on the motion acceleration and anatomy of a participant. However, the physiotherapeutic tests are performed on the muscular groups in different configurations, assuming low acceleration of lower extremity movements.

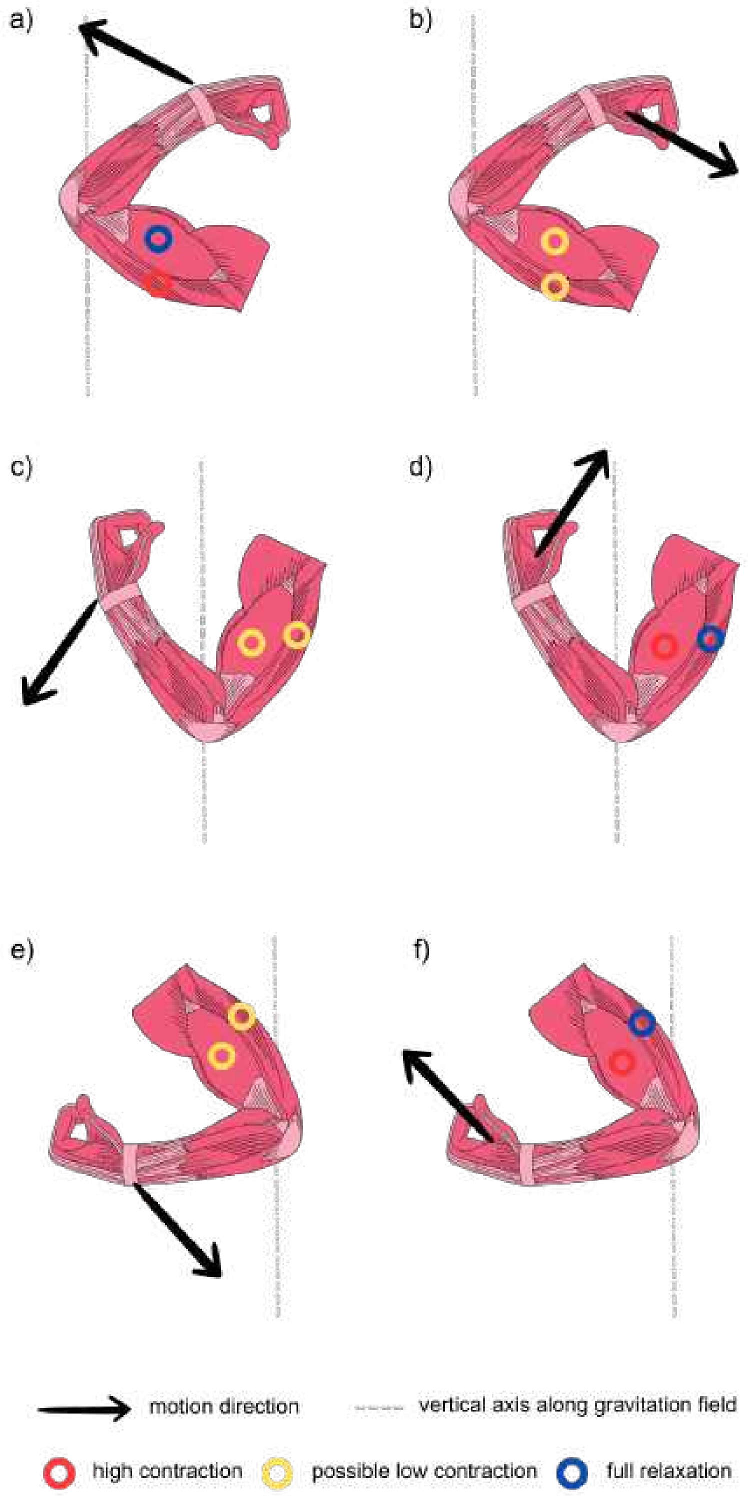


Figure 25: Dependance of the muscular contraction levels on the direction of motion in the corresponding DOF and configuration of the extremity regarding gravitational acceleration vector.

The muscular activity of the participant during conventional therapy of a physiotherapist and during the robot-aided phase is based on the following indicators:

1. $\overline{e}$ - Average muscular activation within the trial session (normalised for every individual);
2. $\overline{\delta e}$ - Average absolute difference in muscular activation within the trial session (normalised for every individual);
3. $T_{c\%}$ - Length of the correct activation calculated according to the formula 9, where t^*_{ij} is the correct activation interval (the intervals where j-th muscular group has the correct level of intentional activation with the stable pace of contraction), while T is the total time of the exercise.

$$T_{c\%} = \left(\sum_{i=1,j=1}^{i=n,j=8} t^*_{ij} \right) / T \cdot 100\% \tag{9}$$

The main correct activation times (t^*_{ij}) are computed as the period between the registered muscular activation points, where the muscular activation of the j-th muscular group fulfils consequent requirements:

1. Antagonist muscular group with expected high contraction exceed the contraction threshold set as $0.5 \cdot \overline{e}$;
2. Agonist muscular groups with expected full relaxation do not exceed the contraction threshold set as $0.5 \cdot \overline{e}$;
3. Muscular groups do not exceed contraction speed (first derivative of the EMG signal) of 10 per sample.

The contraction speed is calculated as the registered EMG signal first derivative according to the formula 10, where e_i is an EMG signal value in the i-th timestamp.

$$\dot{e}_i = \frac{e_i - e_{i-1}}{i - (i-1)} \tag{10}$$

The muscular groups are assigned as agonists or antagonists based on the signum function of the first derivative of the corresponding DOF rotation (see table 11). To eliminate rapid changes in signum within the phases of theoretical no motion with the small vibrations on the motor shaft's rotation, the value of 0 is assigned for derivatives under the set threshold.

The examples of correct activation analyses are visualised for the first subject of the trials in figures 26 - 31. Register phase was the one during recording the motions with the support of the physiotherapist, while the following phase was the one with the active support of the exoskeleton following the recorded trajectories.

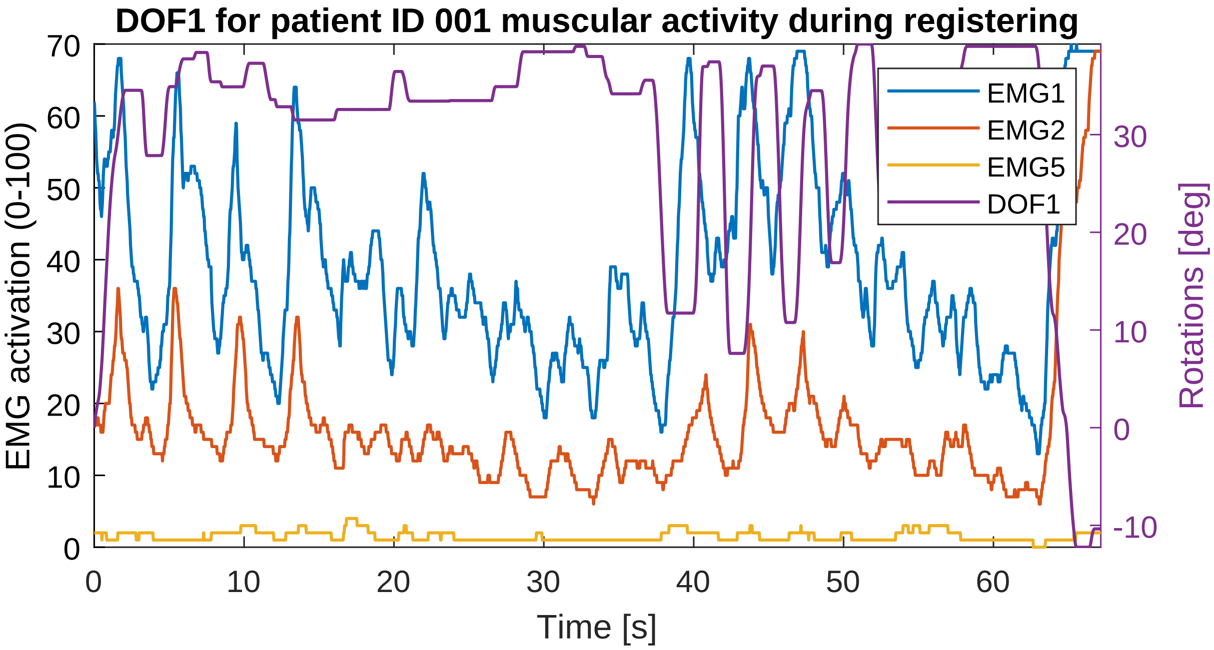


Figure 26: Muscular activity corresponding to DOF1 for participant ID 001 for registering motion.

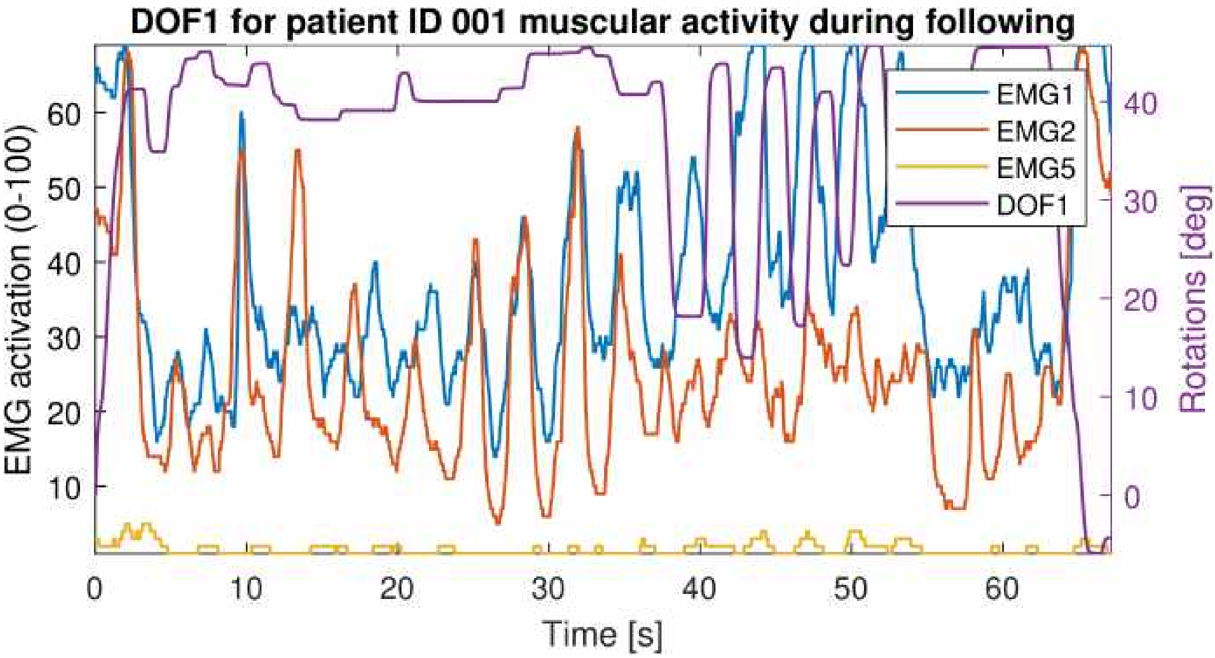


Figure 27: Muscular activity corresponding to DOF1 for participant ID 001 for following motion.

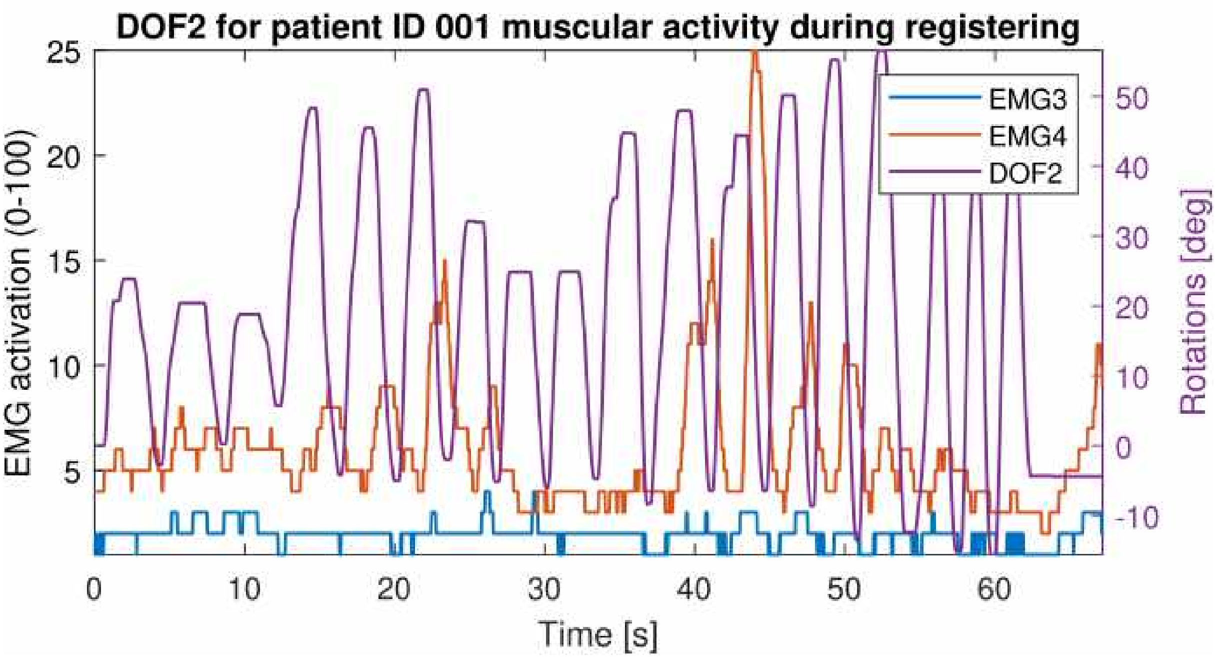


Figure 28: Muscular activity corresponding to DOF2 for participant ID 001 for registering motion.

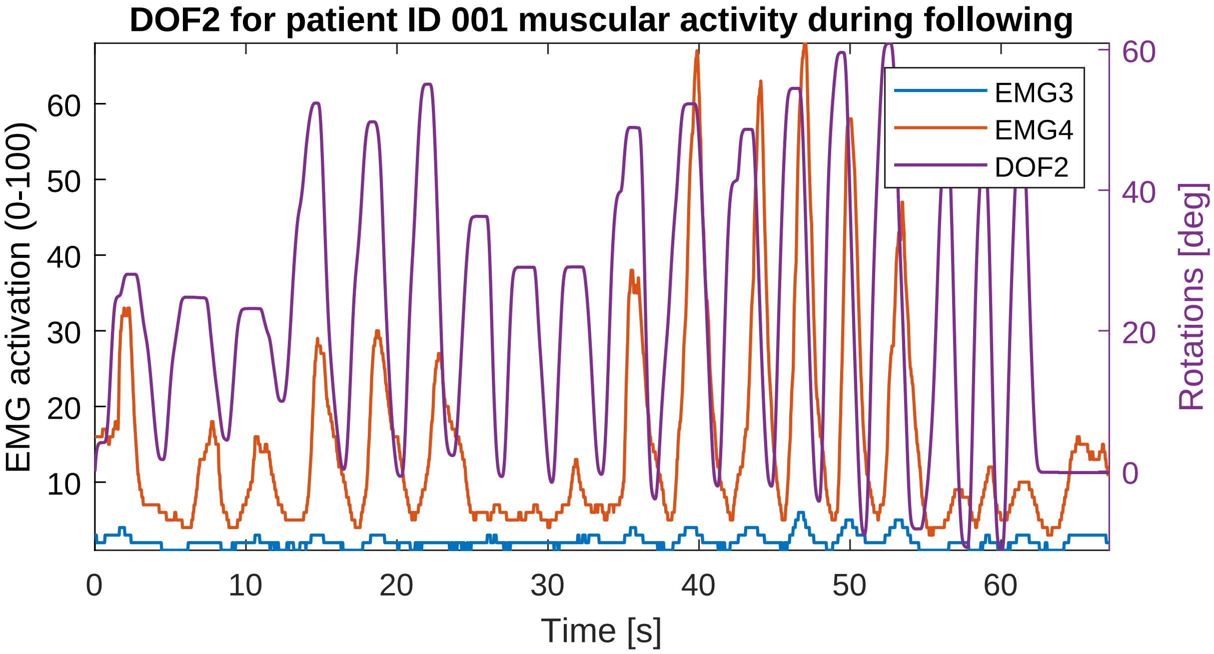


Figure 29: Muscular activity corresponding to DOF2 for participant ID 001 for following motion.

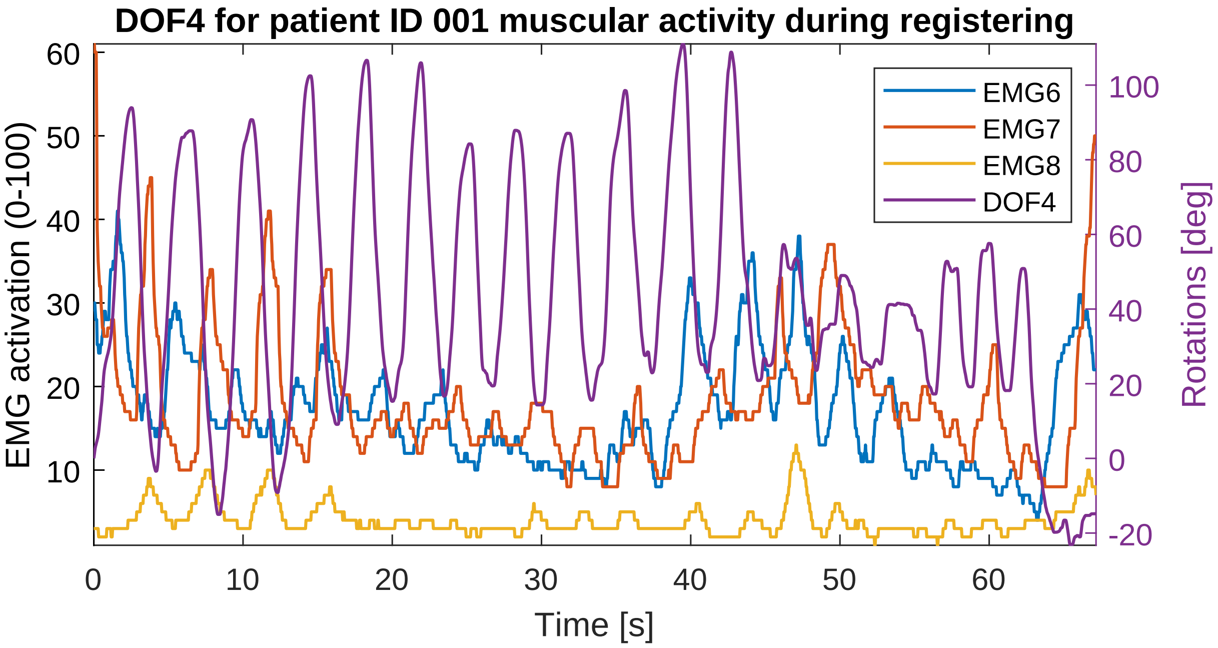


Figure 30: Muscular activity corresponding to DOF4 for participant ID 001 for registering motion.

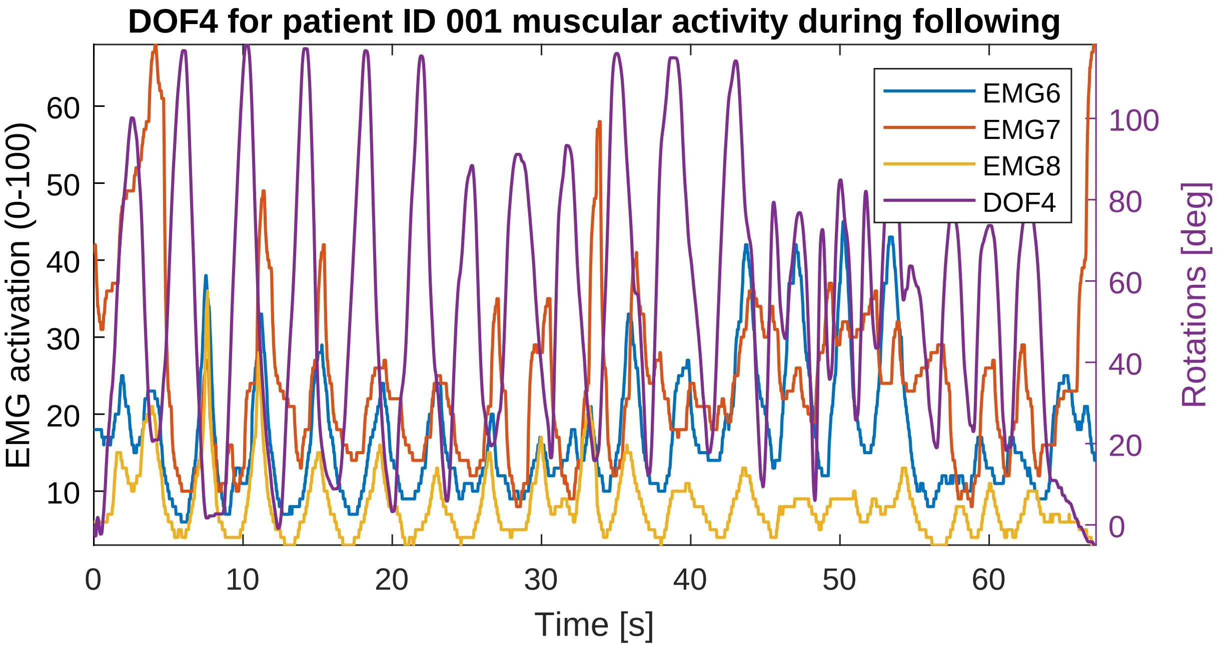


Figure 31: Muscular activity corresponding to DOF4 for participant ID 001 for following motion.

Activations of muscles were analysed for every participant and their every DOF separately. Moreover, for the computation of $\overline{e}$ and $\overline{\delta e}$ indicators, every muscular group for every participant was analysed one by one. The examples of analyses results for differences in muscular activation within registering and following motion phases for the first subject of the trials are presented in figures 32 - 39.

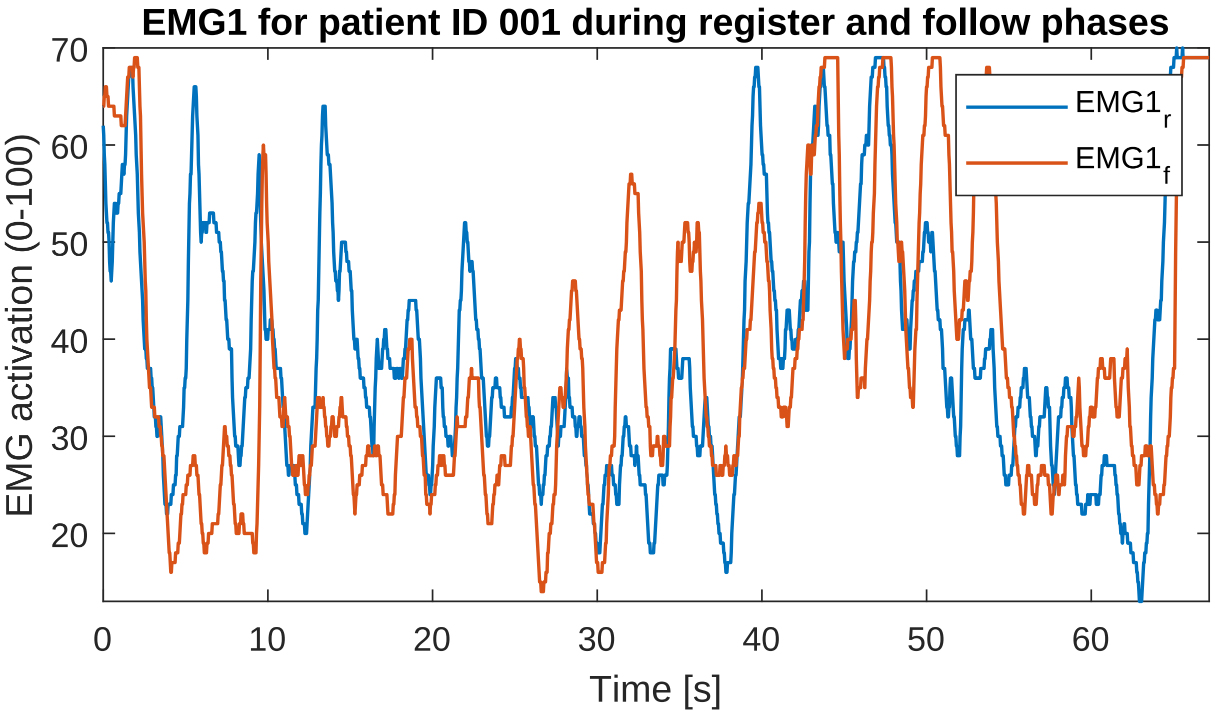


Figure 32: Electrical activity of the muscular group 1 for participant ID 001 compared for registering (EMG_r) and following motion phases (EMG_f).

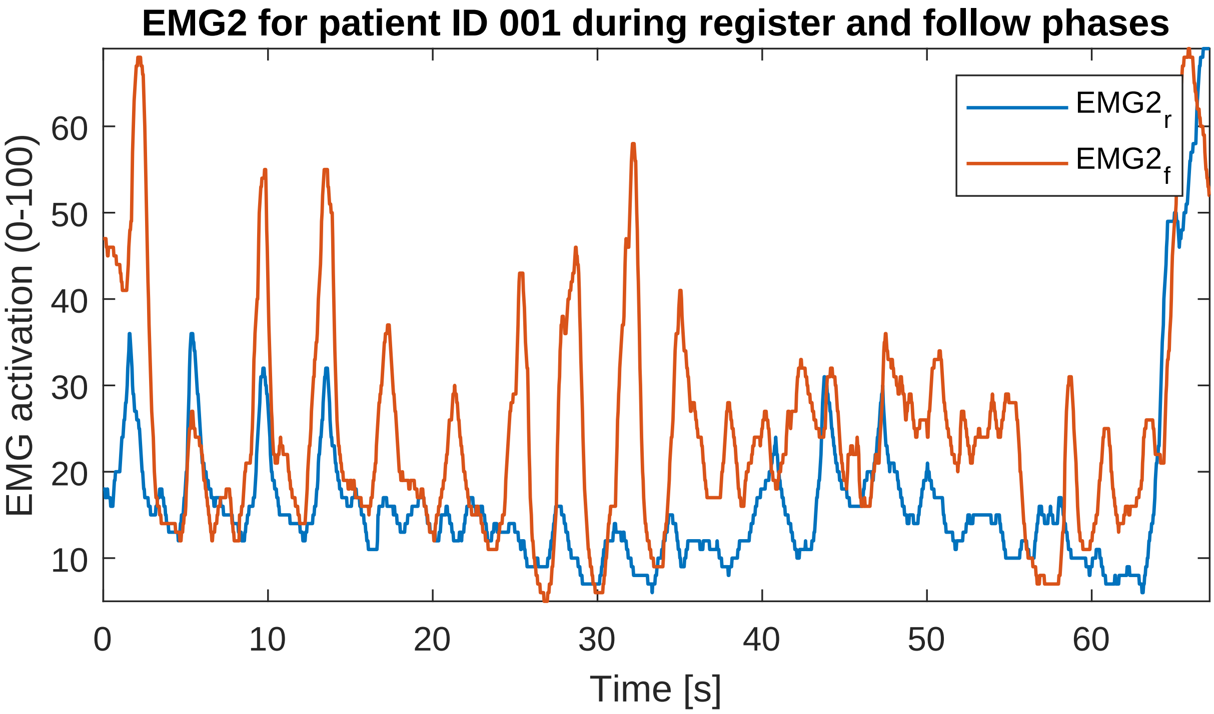


Figure 33: Electrical activity of the muscular group 2 for participant ID 001 compared for registering (EMG_r) and following motion phases (EMG_f).

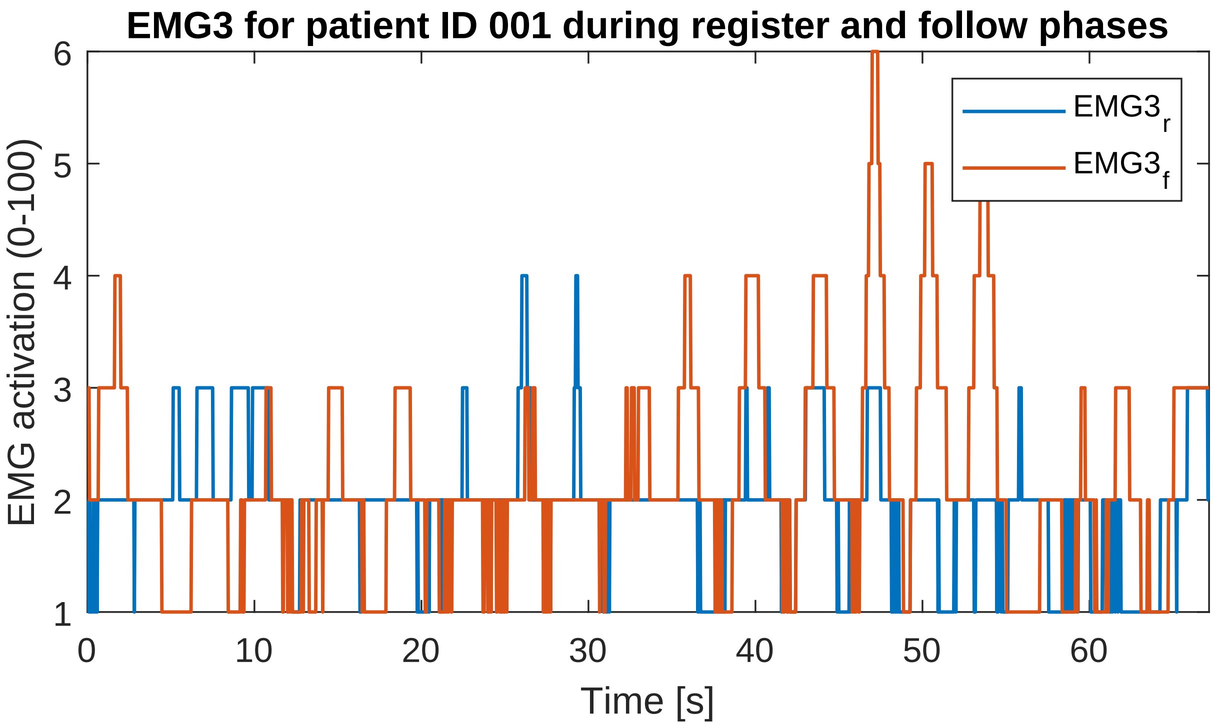


Figure 34: Electrical activity of the muscular group 3 for participant ID 001 compared for registering (EMG_r) and following motion phases (EMG_f).

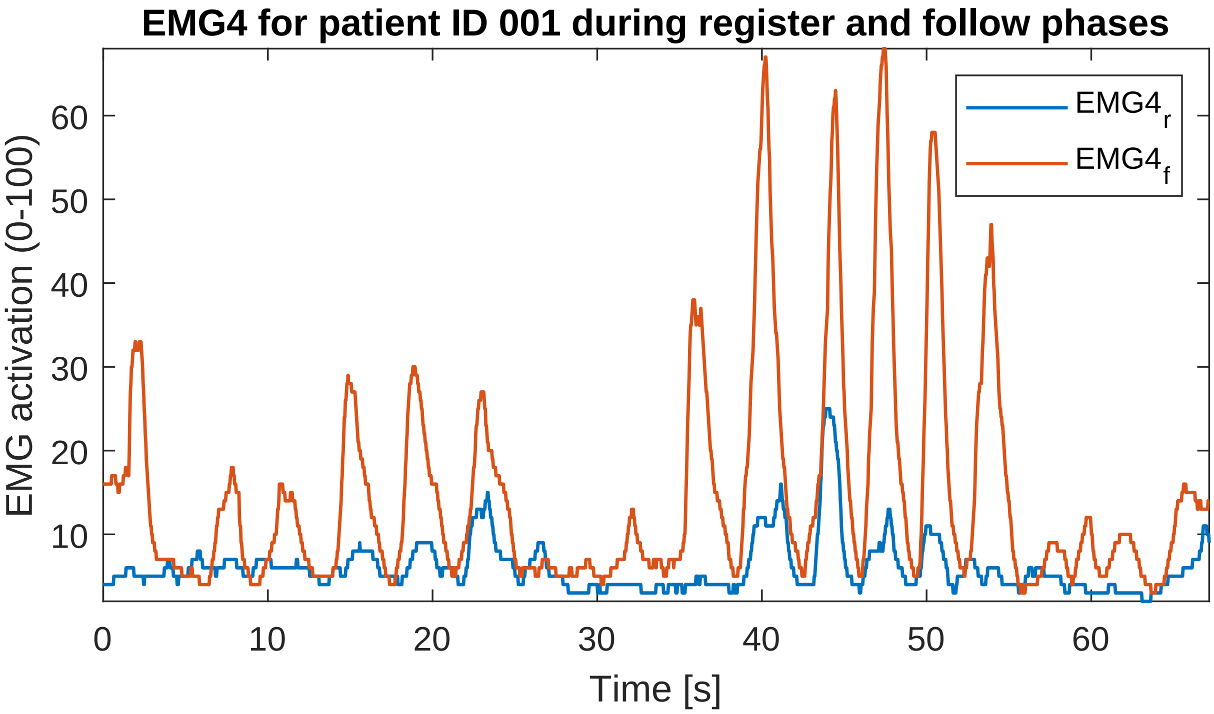


Figure 35: Electrical activity of the muscular group 4 for participant ID 001 compared for registering (EMG_r) and following motion phases (EMG_f).

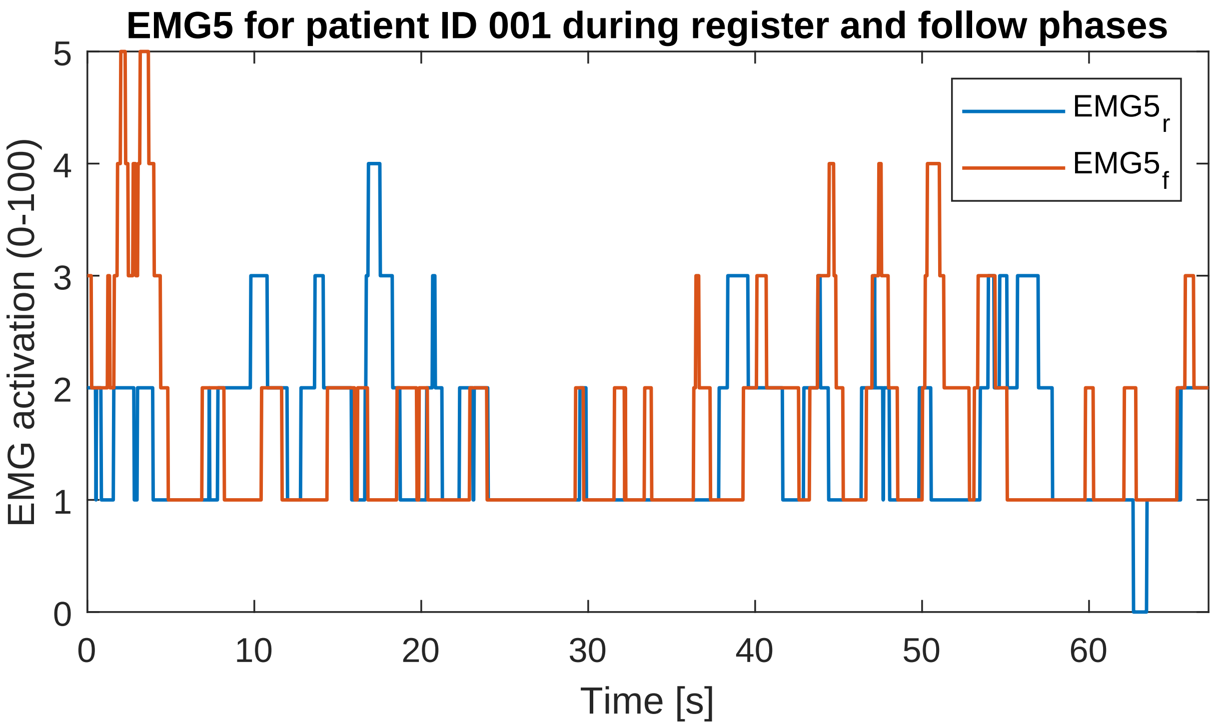


Figure 36: Electrical activity of the muscular group 5 for participant ID 001 compared for registering (EMG_r) and following motion phases (EMG_f).

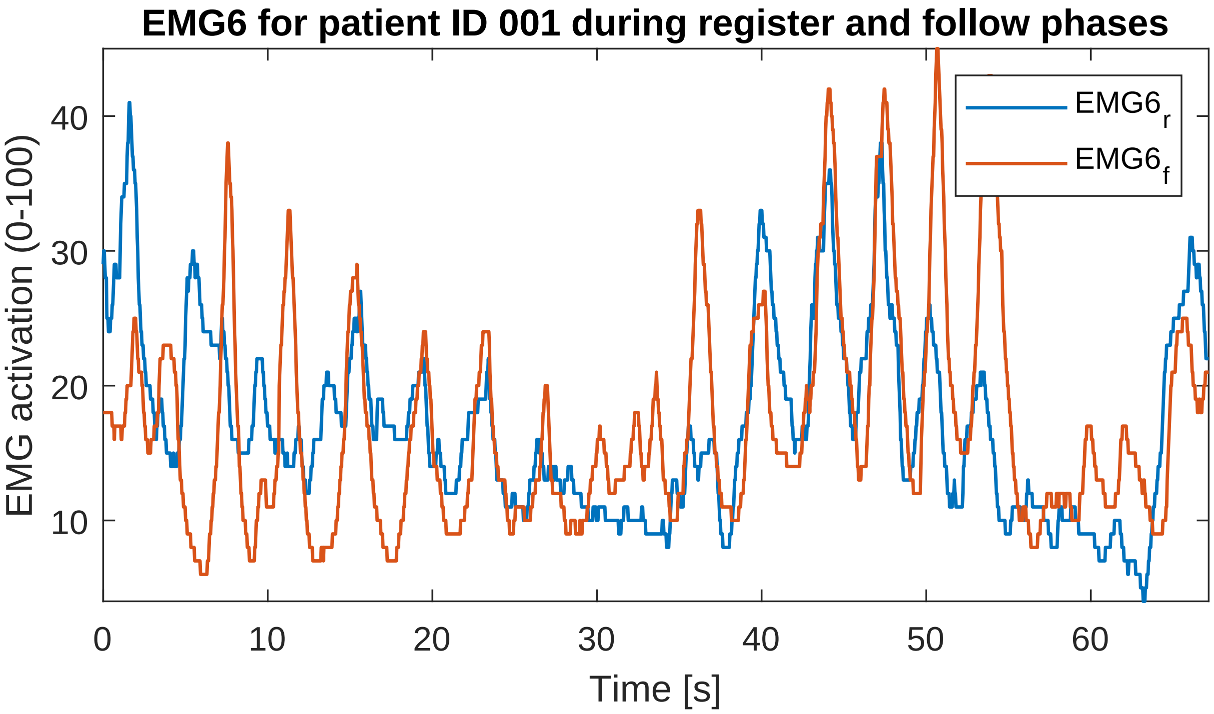


Figure 37: Electrical activity of the muscular group 6 for participant ID 001 compared for registering (EMG_r) and following motion phases (EMG_f).

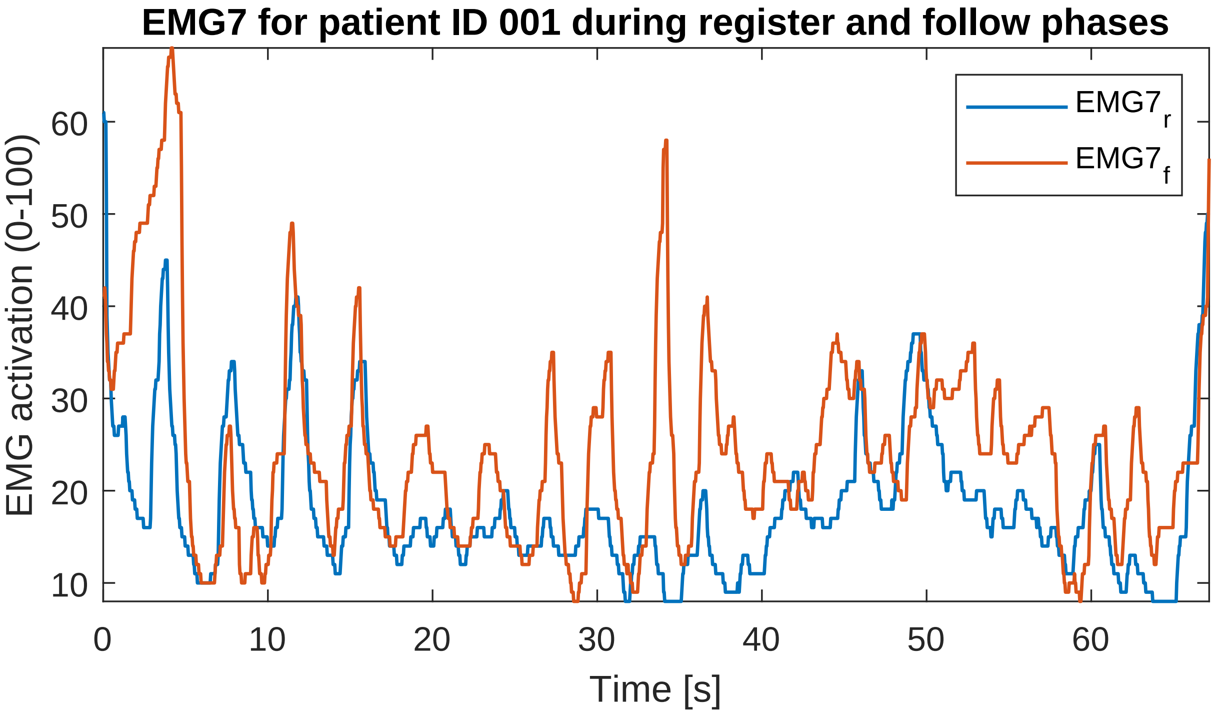


Figure 38: Electrical activity of the muscular group 7 for participant ID 001 compared for registering (EMG_r) and following motion phases (EMG_f).

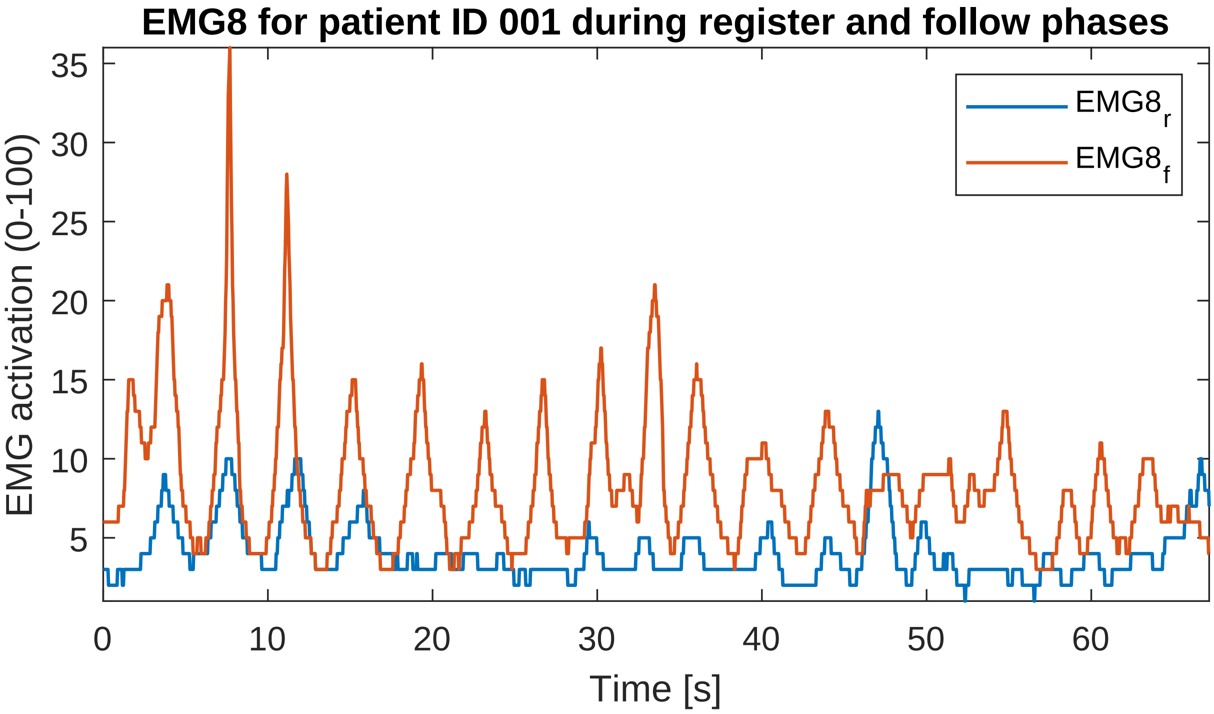


Figure 39: Electrical activity of the muscular group 8 for participant ID 001 compared for registering (EMG_r) and following motion phases (EMG_f).

The final results of the analysis were computed as the average for all the participants (for three repetitions of every motion type each). They are presented for every muscular group separately and as the average from all the muscular groups in table 12 and in figures 40 - 42. The $\overline{e}$ and $T_{c\%}$ indicators are computed for the registering trajectory phase (experimental trial 5) and following trajectory phase (experimental trial 6). $\overline{\delta e}$, as the average absolute difference between two phases, is presented only once.

Table 12: Results of the EMG-based analysis of the muscular activity during the experiments.

	Registering trajectory		**Following trajectory**		
EMG no.	$\overline{e}$	$T_{c\%}$	$\overline{e}$	$T_{c\%}$	$\overline{\delta e}$
1	29.133	66.25%	34.337	54.64%	13.521
2	13.522	88.23%	19.212	80.73%	29.451
3	1.643	93.71%	2.387	93.77%	1.004
4	4.815	94.09%	7.887	92.08%	4.786
5	1.401	93.51%	1.673	93.49%	0.796
6	11.295	90.46%	14.047	88.05%	7.717
7	8.775	90.01%	11.642	88.61%	5.354
8	5.092	94.05%	6.836	92.86%	3.895
Total	9.459	88.79%	12.253	85.53%	5.815

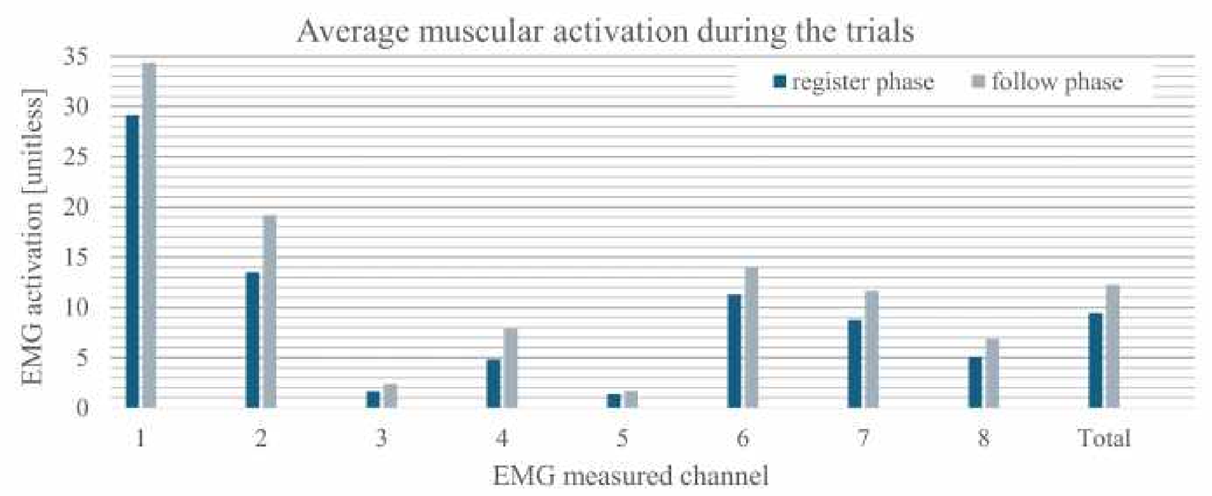


Figure 40: Average muscular activation ($\overline{e}$) during the trials.

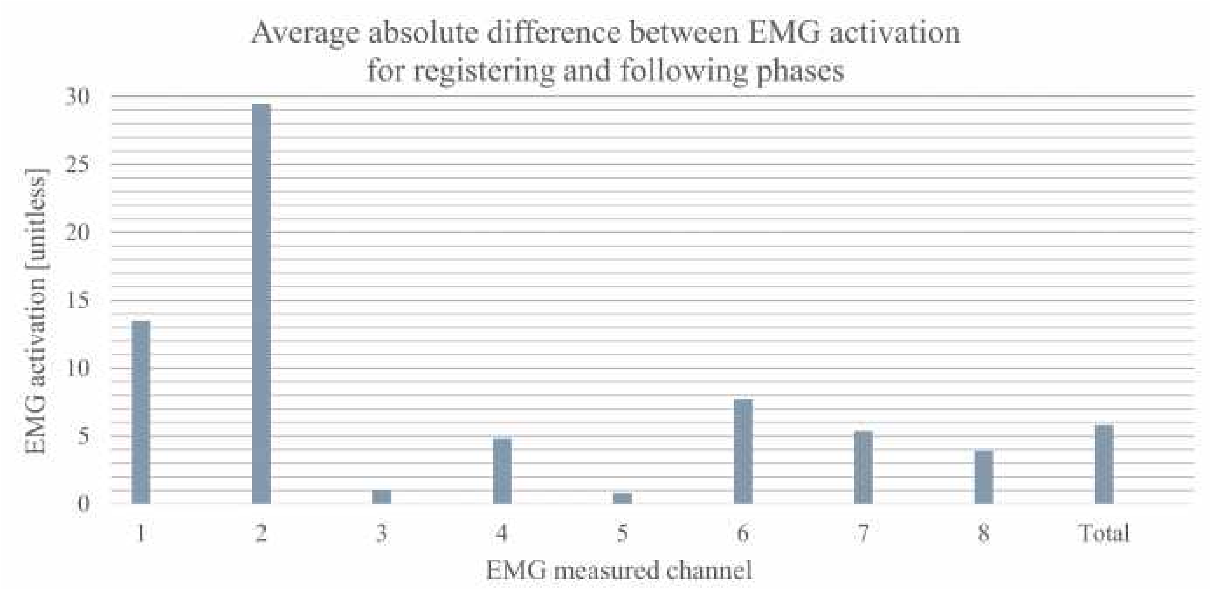


Figure 41: Average absolute difference between EMG activation ($\overline{\delta e}$) for registering and following phases.

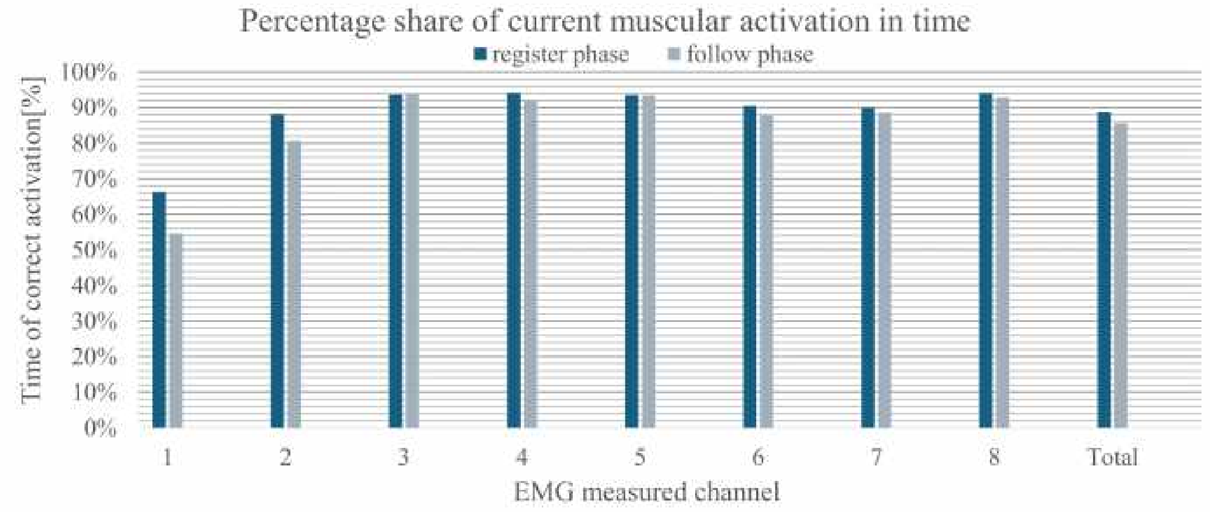


Figure 42: Percentage share of current muscular activation in time ($T_{c\%}$).

For most of the cases, muscular groups cooperated correctly, which can be seen in figures 26 - 31. The muscular contractions were regular with the motion repetitions and generally synchronised between muscular groups corresponding to the single DOF.

As can be observed, activation in the muscular groups 3 and 5 was significantly lower than that of other muscular groups (see figures 40, 34, and 36). This remains in line with the designed test therapy routine, as no additional loads were applied for the exercises. Therefore, the *pectoralis major* and *latissimus dorsi* muscles were less active within motions.

In most of the cases, curves representing muscular activation looked alike. The largest differences can be observed at the initial and last parts of the registered routines, where the motion began or ended in the start position (T-pose). Such an extremity configuration is rarely reached within the whole therapy cycle.

Differences in muscular activation ($\overline{\delta e}$) remain relatively low for the muscular groups 3-8 (see figure 42). However, these are significant for the first two groups (see figure 42). It is worth noting that these are two groups with the highest average activation levels. Nevertheless, the large difference between average activations ($\overline{e}$) in motion registering and following phases can result from part of the exoskeleton weight load exerted by the exoskeleton on the *deltoid* muscle.

The most critical indicator for assessment of therapy correctness is $T_{c\%}$. It reached a satisfactory level of over 85% for all the muscular groups but 1, and 2 in the following trajectory phase (see figure 41). This can be the result of the mentioned overloading of the deltoid muscle. Due to the activation reacting to the additional weight on the shoulder joint, the activation was not as expected within the therapy. For this reason, the initial components of the exoskeleton need to be redesigned to be more rigid. Furthermore, the whole mass of the device should be reduced.

Moreover, the differences between $T_{c\%}$ parameter within registering and following trajectory phases for muscular groups 2-8 are neglectable (see figure 41). This proves that exoskeleton-aided therapy can be comparable to conventional manual physiotherapy when the device does not exert additional force on the user's shoulder.

The impact of the experiments was also validated based on the participants' ROMs. This parameter was measured before and after the experiments. Their comparison results are presented in table 13. The improvements are typical for the short human-assisted sessions, as the one simulated within the experiment. What is important is that the average improvements were positive and did not differ extensively from pre-experimental measurements. Therefore, this also proves that the effects of robot-aided physiotherapy regarding ranges of motion can be comparable with the conventional treatment.

Table 13: Average ROM measured prior and post experiments and their changes within the session.

ROM	**Prior experiments**	**Post experiments**	**Difference**
Shoulder flexion/extension [deg]	192.1(-20.1/+23.9)	199.2 (-18.2/+14.8)	7.1 (-28.1/+24.9)
Shoulder adduction/abduction [deg]	165.7 (-38.7/+14.3)	169.4 (-33.4/+10.6)	3.7(-3.7/+5.3)
Shoulder internal/external rotation [deg]	141.3 (-47.3/+20.7)	153.8 (-42.8/+12.2)	12.5(-9.5/+46.5)
Elbow flexion/extension [deg]	139.8 (-9.8/+10.2)	141.4 (-6.4/+8.6)	1.6(-12.6/+6.4)
Pronation/supination [deg]	164.7 (-14.7/+25.3)	170.1 (-15.1/+19.9)	5.4(-7.4/+16.6)
Wrist flexion/extension [deg]	150.8 (-29.8/+34.2)	156 (-21/+16)	5.2(-40.2/+13.8)
Wrist adduction/abduction [deg]	53.4 (-15.4/+18.6)	55.7 (-13.7/+19.3)	2.3(-14.3/+14.7)

6.6 Quality of the control system

The quality of the control during the robot-aided phase is based on the following indicators:

1. $\overline{\delta\varphi}$ [deg] - Average absolute angular inaccuracy between the registered trajectory and the one followed by a participant with an exoskeleton;
2. σ_φ [deg] - Standard deviation of absolute angular inaccuracy between the registered trajectory and the one followed by a participant with an exoskeleton;
3. $\delta\varphi_{max}$ [deg] - Maximum absolute angular inaccuracy between the registered trajectory and the one followed by a participant with an exoskeleton.

Differences in the trajectories realised within registering and following phases were analysed for every participant's DOF individually. The examples of analysis results for the first subject of the trials are visualised in figures 43 - 45.

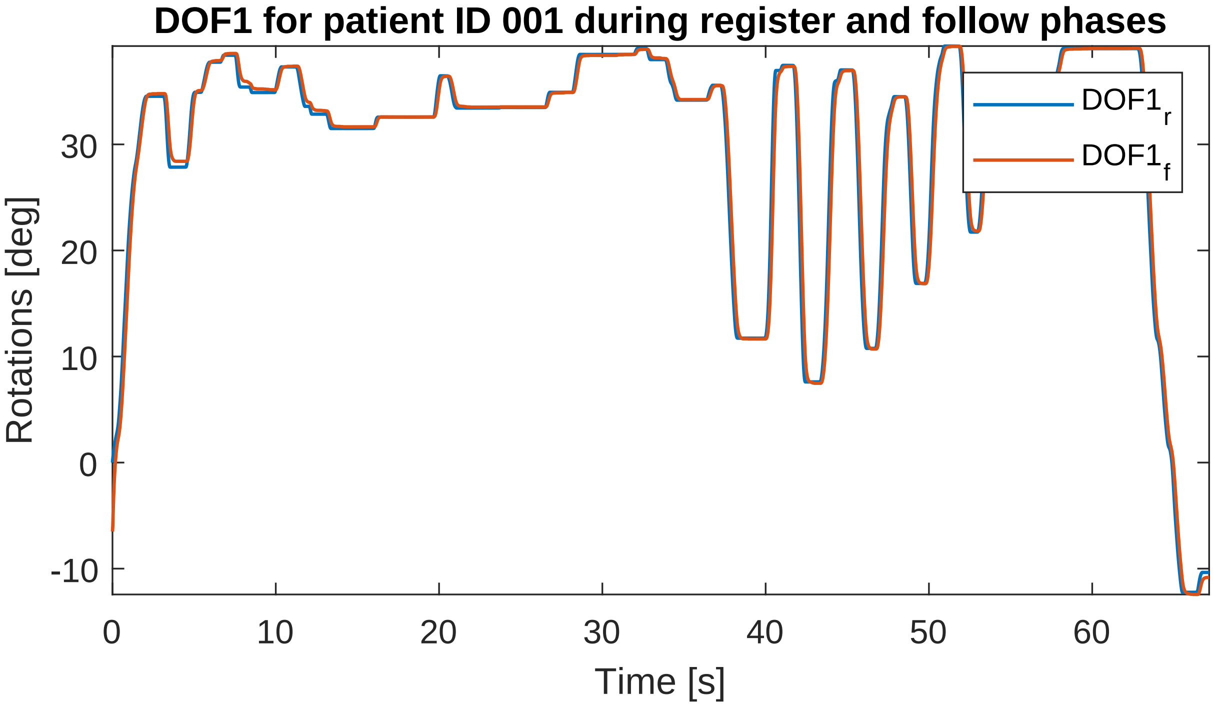


Figure 43: DOF1 rotation for participant ID 001 compared for registering (DOF_r) and following motion phases (DOF_f).

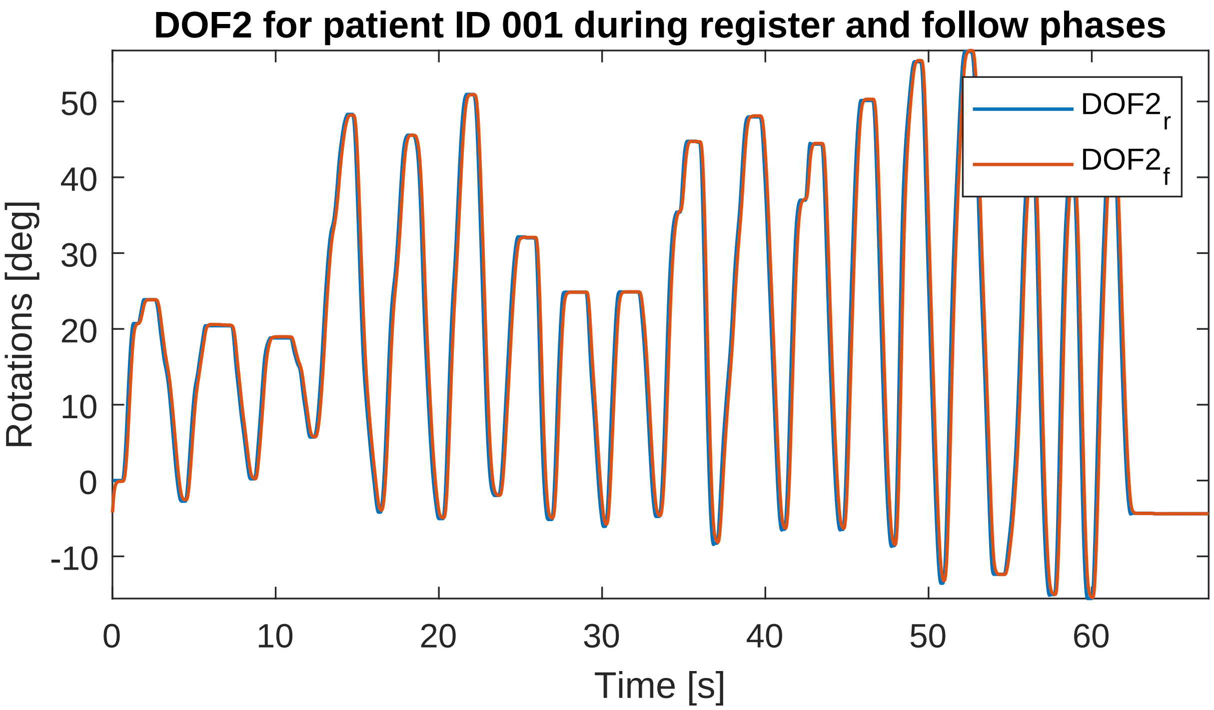


Figure 44: DOF2 rotation for participant ID 001 compared for registering (DOF_r) and following motion phases (DOF_f).

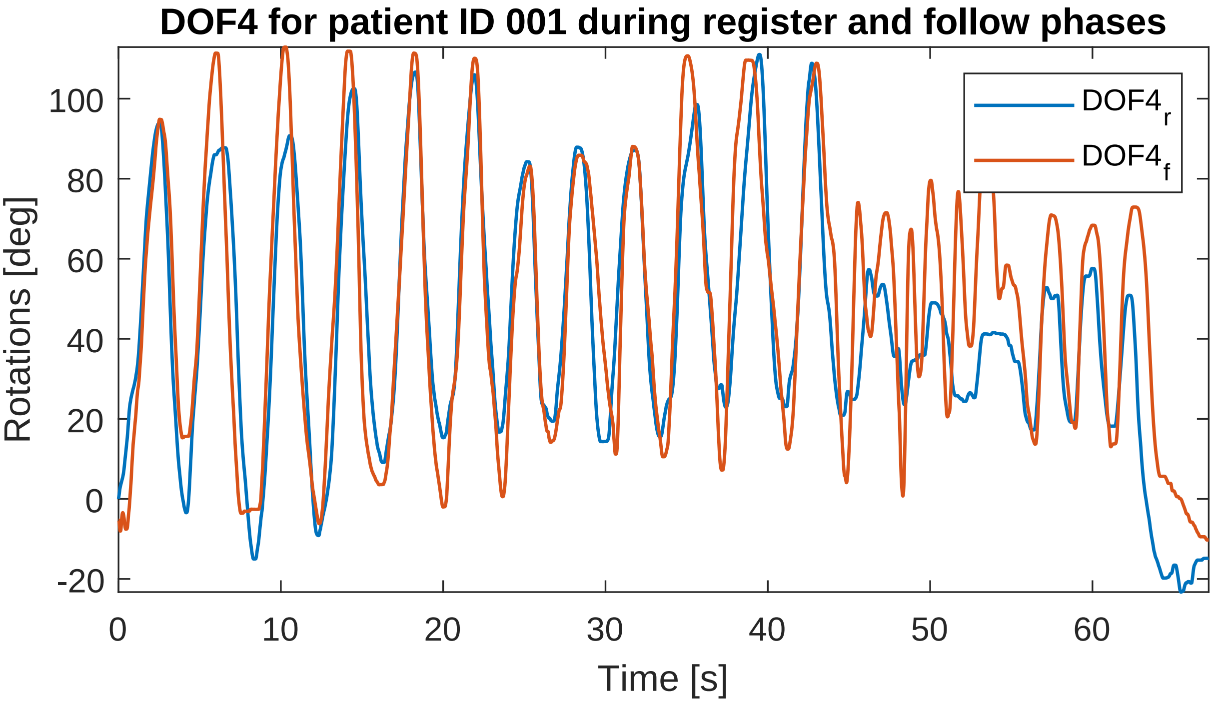


Figure 45: DOF4 rotation for participant ID 001 compared for registering (DOF_r) and following motion phases (DOF_f).

The mentioned parameters are calculated initially for every participant individually and then derived for the whole group. The driven joints are distinguished from one another within the analysis. Hence, every indicator is computed for these separately, which results in presenting them in a three-variable vector. The computed values for all the participants on average are compared in table 14.

Table 14: Results of the analysis of control quality during the robot-aided physiotherapy.

DOF no.	$\overline{\delta\varphi}$ [deg]	σ_{φ} [deg]	$\delta\varphi_{max}$ [deg]
1	0.669	1.133	11.794
2	2.066	2.361	12.27
4	22.154	23.766	112.469
Total	8.3	9.087	45.511

As can be seen in figures 43 and 44, the following of the trajectory for the shoulder joint was realised with very high accuracy. The differences appeared after rapid accelerations or decelerations of certain DOFs (e.g. see figure 43 2-12 s). This error could be further minimised with finer tuning of the PD controller. However, the results obtained for DOF1 and DOF2 remained on an acceptable level.

Even the maximum difference during the dynamic following was acceptable, not exceeding 12.27 degrees. However, for patients with limited ROM, additional safety region monitoring should be implemented. However, the exercise motions performed within the simulated therapy were adjusted to the capabilities of healthy humans. Therefore, their velocity was high, which resulted in kinematic inaccuracies.

The worst results appeared for the elbow joint, with an average error of over 20 degrees. Obtained accuracy did not meet the criteria enabling accurate repetition of the recorded exercises. This was due to the excessive reaction bending moments frequently appearing on the drive's shaft. When this occurred, the drive was locking and did not follow the rotation trajectory correctly. The exoskeleton needs to be redesigned in this joint and provided with another driving system.

Even though the elbow joint did not reflect the registered motion correctly, the activation of correlated muscular groups remained at the correct level (see table 12 and example in figure 26). Therefore, the exercises with the exoskeleton would be appropriate in terms of muscular effort but would not engage the elbow joint in the satisfactory range.

6.7 Individual perception

The tests were followed up with surveys based on participants' feedback. These included the following aspects:

- Physical feelings - particularly regarding the components interfacing directly with the extremity and joint misalignments or dimensional inaccuracies;
- Neurological feelings - particularly regarding motion sickness while using a VR headset;
- Difficulties in understanding the treatment or operating the system.

The results of this questionnaire were analysed as qualitative data. Hence, they are used to define possible further system modifications.
The main insights of the investigation are presented below:

1. All the participants reported misunderstanding 2D visualisation with the bar charts corresponding to the single DOFs. However, they claimed that following just a single DOF method is better than using phantom-based 3D or VR visualisation. For this reason, it should be considered for use within a single DOF mobilisation exercise. These can be performed at the beginning of the treatment, especially to strengthen the shoulder joint.
2. Motion sickness affected one participant. However, he performed the activity while visualising with VR for over 10 minutes. The situation has not been repeated for any other visualisation method. For this reason, further trials should consider substituting VR with AR.
3. Multiple participants reported difficulty activating arm and forearm rotations with the attached passive exoskeleton. This problem was not reported while using the active exoskeleton. Therefore, the lower activation torques for these movements are confirmed as assumed at the beginning of the design. Moreover, for further motion modelling, inertial measurement units (IMU) with the MBD model corresponding to the exoskeleton is used.
4. Participants reported a general problem while performing pure shoulder flexion until aligning parallel to the horizontal plane followed by pure horizontal adduction. This is a result of the singularity coming from aligning axes of the DOF 1 and DOF 3, while DOF 2 can be in multiple configurations. The problem does not exist in the active exoskeleton, as DOF 1 is fully controllable. The strategy of controlling DOF 1 should be based on the direction of rotation in DOF 2, which is expected in the next steps.
5. Multiple participants reported that the DOF1 motion was the hardest to control. It is important, as the configuration of the subsequent DOFs depends strictly on its rotations. However, observation of registered results proved that the obtained accuracy was at a very high level (below one degree), which should not affect the physiotherapy process. The inaccuracies from the soft elements' flexibility can exceed this value multiple.
6. All of the participants reported problems with reaching tasks with the ExoReha support on the distal regions on the left side of their body. This was the result of the plain bearings' bulkiness, resulting in the collision of the DOF3 with their rib cage. The problem was encountered while performing scratching of ribs but can exclude multiple not-tested task-oriented tasks.
7. Multiple participants reported that the tasks realised in the parasagittal plane were easier to realise, as the resultant moments were reducing elbow drive torque other-

wise. For this reason, it is expected that coming back to the start position at the end of the trials resulted in the worst following accuracy in DOF4.

8. While repeating the recorded trajectories with the ExoReha exoskeleton, participants had no exercise visualisation. Therefore, they repeated exercises based on verbal information from a physiotherapist and the sensed drive activity. Their use of free sliding bearings was initially unintuitive, particularly for motions reflecting scratching ribs or brushing. However, the correctness of the performed motions increased with the number of repetitions. Despite difficulties, the application of these structures enables anyone to use the exoskeleton, even if they have limited ROMs. This aspect is critical for patients who cannot straighten their extremities to attach the device.
9. Most of the participants reported that due to the too-low rigidity of the first body of the exoskeleton, some part of the device's weight was imposed on their musculoskeletal system. The resultant forces were sensed mainly in the shoulder girdle and abdomen regions. Exercising with such for a long time will be too tiring, especially for patients with disabilities.
10. Most of the participants reported that exercising with an exoskeleton required their physical activity to be bigger than they expected - especially for the elbow joint. However, all of them claimed that the movements performed were significantly easier due to the actuation of the device.

6.8 Summary

This section describes the complete process of the experimental phase. It includes methodology, setup description, results, and the outcomes discussion. During the investigation, a quantitative analysis of the measured indicators was performed. This includes an analysis of the trajectories' kinematic reflection and a patient's muscular activation within the motion. Moreover, the qualitative insights were formed based on the post-trial survey with participants. These all are the bases for further research and improvements in the exoskeleton's design.

Moreover, the results of the investigation enabled the validation of the dissertation theses:

1. The rehabilitation exoskeleton loads the musculoskeletal system of the patient comparably to the physiotherapist;
2. Use of the VR/AR motion visualisation provides better accuracy of motion-path following.

Thesis 1 was confirmed with the disclaimer that the device must not exceed additional weight on the patient's musculoskeletal system. Due to this fact, the exoskeleton will be modified in the follow-up R&D (research and development) works.

Thesis 2 was denied. The results obtained for 3D visualisation on the flat display were

comparable with the ones obtained with the VR. Moreover, the use of VR brings additional risk of negative side effects.
The impact of the investigation results on further works is presented in the following section.

7 Conclusions

7.1 Introduction

The following section encloses the thesis. It summarizes the simulation, design, prototyping, and experimental works undertaken within the project. The results present the study's limitations, main insights, planned research continuation, a commercialisation plan for the exoskeleton, and the impact on the author.

7.2 Outcomes of the project

Within the project, the following stages were completed as planned:

- In-depth identification of the need;
- Modelling task-oriented kinesiotherapy sessions;
- Kinematics and dynamics simulations of the system;
- Mechanical and electronic design;
- Construction of the exoskeleton;
- Development of the control system and an HMI;
- Designing EMG tracking system;
- Implementing EMG tracking for performance assessment;
- Building a VR application for visualisation of the treatment;
- Implementing VR for the treatment;
- Experiments on patients' biomechanical performance;
- Validation patients' individual perception and side effects.

The constructed prototype was integrated with the biomedical signals measurement system and the VR visualisation environment. Then, it was used for the experimental phase, which proved that exoskeleton-aided therapy could affect patients comparably to conventional physiotherapy in terms of muscular activation. However, the other parts of the investigation disproved the advantage of the VR environment compared to 3D models on flat displays for therapy visualisation.

The concept of the 3D-printed exoskeleton confirmed that the powder technology is durable enough to be used for rehabilitation devices. However, it is critical to provide sufficient rigidity, not only cohesion of the parts. In case of excessive flexibility, the exoskeleton can press the user's extremities and force irregular loads on the muscular system.

An EMG tracking system was integrated into the exercise assessment system and enabled the analysis of muscular activity levels. Moreover, the activations were analysed regarding current motion states and allowed validation of whether they are correct or incorrect regarding triggered motion. The original indicator of the correct activation for an exercise loop cycle was proposed. This can be used to optimise the treatment and assess progress. Thanks to maximising its value, a patient will recall correct motion patterns while activating joints and increasing muscular strength.

Apart from the plan, the system was integrated with its digital twin and the predictor of possible hazardous configurations. These tools are essentially beneficial for remote physiotherapy and teleoperation over exoskeletons. The method can facilitate therapy for people with low mobility and living in less populated areas.

Summarising, the main insights from the research are:

- Exoskeletons can provide physical support comparable to the one of the physiotherapist while monitoring performance at a higher level;
- VR environment does not increase understanding of exercises compared to the same visualisation displayed on the flat screen. However, both of these are more understandable than 2D slider visualisation for exercising multiple DOFs at the same time. For the single joint mobilisation, 2D slider visualisation is preferable;
- 3D-printed elements of exoskeletons should rather be manufactured with powder technologies than fused filaments. The latter can cause decohesion between layers during occurring share load states;
- 3D-printed elements give an opportunity to exchange the components in case of wear easily. Moreover, some of these can be redesigned for patients with outstanding anatomy;
- Free degrees of freedom initially cause lower precision in task-oriented exercises. However, they enable the use of the device by patients not able to obtain the initial position (with straight extremities) and allow performing activities naturally, not memorising wrong motion patterns;
- EMG activation levels are significantly different for different muscular groups and users. Nevertheless, the use of the presented algorithm can enable the automatic setting of the expected activation thresholds based on the average activity and assessment of the treatment efficacy;
- Bulkiness of the design, its weight, and relatively low elbow joint moto torque caused some problems in the accuracy of the following trajectory. The identified problems and planned improvements are presented in the further subsections.

7.3 Limitation of the project

The project resulted in proving only one of the two initial theses. The other was considered false, as the results did not present the expected tendency.

Within system prototyping and experimental trials, multiple failures appeared. They were overcome and will be used to learn from experience according to the PRINCE2 second principle. The most important are as follows:

- 3D printing with FFF/FDM technologies are not durable enough to shear and result in decohesion between printed layers;
- Unknown brand servodrives can perform with lower parameters than presented in the technical documentation due to their electronics. Moreover, reclaiming the ones

purchased out of the European Union is difficult. Within the experimenting with the drives, the Polish company developing controllers for them was identified. The use of their solutions significantly increased obtained accuracy and repeatability;

- Too bulky design hinders some of the task-oriented exercises. A further version of the exoskeleton should be minimised, especially in terms of the free, sliding bearings;
- Cable connection between the EMG electrodes, sensors and processing boards increases electrical noise in the system. Moreover, an extremity's mobility was also limited, even though the sensors were placed on the belt. Measuring with wireless devices was much more convenient, and the signal obtained was clearer. However, sensors placed directly on the skin sometimes interfered with the exoskeleton attachments;
- The motor of the elbow joint was not strong enough for the forearm-supporting construction;
- CAN communication and serial power supply ease cable transmission among the system. However, the series large power supply does not work well for small electrical connectors in integrated drives of high-torque motors. Moreover, the motor electrical connectors had a tendency to damage during dynamic motions. The motors should have an additional locking system for the cables;
- The elements with sliding regulation did not work well with the aluminium rods embedded. Moreover, their plastic part was too thin and vulnerable to bending moments. The element between the first two motors was also not rigid enough. These parts of the exoskeleton will be redesigned during the project continuation;
- The prototyped design worked fine while attached to the frame, but it was too heavy to be used while placed directly on a user's shoulder girdle;

Moreover, the exoskeleton was designed for passive therapy, and it did not involve any sensors for detecting the user's intention. During the investigation, the possibility of using real-life and modelled comparisons of dynamics, as well as EMG signals for the intended motion recognition, was considered. The theoretical models should be implemented to enhance the capabilities of the system for active physiotherapy.

Furthermore, it is worth noticing that the experiments were conducted on a limited number of young people. The results were consistent enough to observe general tendencies. However, after the improvements mentioned, the results should be validated for larger, more diverse groups. The further research plans are described in the following sections.

7.4 Prototype and commercialisation plans

The device will be redesigned according to the directions presented above. It is strictly connected with one of the author's research grants mentioned in the following section. Moreover, an advanced control algorithm will be implemented. This should provide active physiotherapy mode combined with smart assessment of the patient's performance and real-time adjustment of the exercising settings.

The development of the technology was combined with collaborating with numerous physiotherapists and medical doctors. Within the consultations, contacts with potential future customers were established. It is expected to deliver the final prototype at the technology readiness level 7 until April 2026 and then start certification of the class 2b medical device. According to the commercialisation plan, an Institute spin-off will be formed to deliver the innovation to the market.

To validate interest in the exoskeleton, the prototype was exhibited during multiple events, including:

- „Science for Society" Congress (Polish: „Nauka dla Społeczeństwa", 2023, Warsaw, Poland, see figure 46);
- International Exhibition of Inventions (2024, Geneva, Switzerland);
- European Association of Research and Technology Organisations Conference 2024 (2024, Warsaw, Poland);
- Meeting with European Space Agency Polish astronaut, Sławosz Uznański (2024, Warsaw, Poland).

The experimental setup presented in this thesis was also used to conduct multiple tutorials for students. This resulted in some of them becoming researchers in the field of rehabilitation technologies and working on further developing this device.

Figure 46: Presentation of the exoskeleton during „Science for Society" Congress 2023 at Warsaw University of Technology.

Moreover, the design was presented during more than ten scientific conferences and trainings. Among others, these include:

- AUTOMATION conference (2022, Warsaw, Poland);
- Young Scientist Congress (2022, Warsaw, Poland);
- Aalborg Symposium in Advances in Rehabilitation Robotics (2023, Aalborg, Denmark);
- XXXIII Polish Conference on Biocybernetics and Biomedical Engineering(2023, Łódź, Poland);
- Medical Robots Conference (Polish: „Konferencja Roboty Medyczne", 2023, Zabrze, Poland);
- „Innovation, Interdisciplinarity, Internationalization" panel discussion during Warsaw Medical Expo (2023, Nadarzyn, Poland);
- International Conference on Mechatronics and Robotics Engineering (ICMRE, 2024, Milan, Italy);
- „Medical robotics" EDIH training (2024, online).

The overall research, exoskeleton and connected designs were also awarded the following prizes (see appendix R):

- Main award of the „Young Promoter of Poland" (Polish: Młody Promotor Polski) contest organised by Polish First Lady's (2024, Warsaw, Poland);
- Award from *Polish Chamber of Patent Attorneys - International Fair of Inventions and Innovations INTARG* (2024, Katowice, Poland);
- Gold medal from *University of Sibu* (2024, Geneva, Switzerland);
- Bronze medal - *International Exhibition of Inventions* (2024, Geneva, Switzerland);
- Gold medal - *International Intellectual Property, Invention, Innovation and Technology Exposition in Bangkok* (2024, Bangkok, Thailand);
- Gold medal from *National University Science and Technology Politechnica Bucharest* (2024, Bangkok, Thailand);
- Special award from *Toronto International Society of Innovation & Advanced Skills* (2024, Bangkok, Thailand);
- Special award from *Research Institute of Creative Education* (2024, Bangkok, Thailand);
- Main award in the „Student-Inventor Competition" (Polish: Konkurs Student - Wynalazca, 2024, Kielce, Poland);
- Award in the „Directions of Activities of the Łukasiewicz Research Network" category in the „Five Years of Implementation Doctorates" competition (Polish: „Pięć Lat Doktoratów Wdrożeniowych", 2022, Warsaw, Poland);
- Silver medal - *16. International Exhibition of Inventions IWIS* (2022, Warsaw, Poland);
- Gold medal - *European Exhibition of Creativity and Innovation (2022, Iasi, Romania)*;
- Silver medal - *15. International Fair of Inventions and Innovations INTARG* (2022, Katowice, Poland).

The aspects mentioned above prove that the developed technology is of great interest and is considered a tool for the physiotherapy of the future. For this reason, the results of the doctorate are not only of scientific value but also implementable.

7.5 Further investigation

The continuation of the research is planned in two areas - development of rehabilitation exoskeletons and technologies assisting modern physiotherapy. The latter contains biomedical signals monitoring for exercise assessment and safety monitoring, digital twins for teleoperation, and intelligent algorithms for automating the therapy.

So far, the results of the research project were the base to apply for the two granted research projects:

1. „Smart exoskeleton for remote rehabilitation with the digital twin technology" – SmartEx-Twin project, financed in 2023-2025 (265,800 EUR), in the scope of sci-

entific research and development works by the National Center for Research and Development (funding programme 5th Call for Proposals Poland-Turkey, contract number POLTUR5/2022/81/SmartEx-Twin/2023) and by The Scientific and Technological Research Council of Türkiye (Project Number: 122N152).

2. „Development of a universal and lightweight construction of rehabilitation exoskeleton with a control algorithm dedicated to remote, home and task-oriented rehabilitation" – SmartEx-Home project, financed in 2024-2026 (1,793,900 PLN), in the scope of scientific research and development works by the National Center for Research and Development (funding programme LIDER XIV, contract number LIDER14/0196/2023).

The author of this dissertation is a vice project leader of the first project and the project leader of the second project. Therefore, the continuation of the research will be strictly connected to these projects, and will contain the following R&D works:

1. SmartEx-Twin project
    (a) Designing the exoskeleton of a lower extremity;
    (b) creating the technology of telerehabilitation based on the manual interaction with the exoskeleton digital twin in VR;
    (c) Developing the technology for treatment optimisation and automatic safety monitoring based on EMG and EEG signals.
2. SmartEx-Home project
    (a) Minimising mass and bulkiness of the *ExoReha* exoskeleton;
    (b) Adjusting its structure to be used while attached to a bed or a chair;
    (c) Modelling task-oriented exercises as joint trajectories;
    (d) Developing control algorithm based on learning motion classification and smart goal functions, which will adapt to any new trajectory registered manually by dragging the physical exoskeleton by a physiotherapist.

7.6 Summary

The planned work for the investigation was completed. This resulted in confirming one of the initial theses and denying the other. Apart from the successes of the R&D process, the limitations of the study and its problematic aspects were formed. They will be used for further improvements in the exoskeleton design and the following projects acquired by the author. As the doctorate was realised within the Implementional Doctorate programme, its results are planned to be commercialised as the original product of the Institute's spin-off. Beforehand, further development and certification of the system as a medical device is required. These will be realised simultaneously with the next research projects described.

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Abbreviation List

AI Artificial Inteligence
ADL Activity of Daily Living
AR Augmented Realit
CAD Computer-Aided Design software
CAE Computer-Aided Engineering software
CAGR Compound Annual Growth Rate
CAM Computer-Aided Manufacturing software
CAN Controller Area Network (vehicle bus standard)
DOF Degree of Freedom
DH Denavit–Hartenberg
EEG Electroencephalography
EMG Electromyography
FDM Fused Deposition Modeling
FEM Finite Element Method
FES Functional Electrical Stimulation
FFF Fused Filament Fabrication
GUI Graphical User Interface
HMI Human-Machine Interface
ICT Information and Communications Technology
IMU Inertial Measurement Unit
IoT Internet of Things
ISOM International Standards of Measurement
MBD Multibody Dynamics
ML Machine Learning
MR Mixed Reality
NARX Nonlinear Autoregressive Exogenous Neural Network
PI Proportional–Integral Controller
PID Proportional–Integral–Derivative Controller
ROM Range of Motion
ROS Robot Operating System (software)
sEMG Surface Electromyography
SLS Selective Laser Sintering
UI User Interface
UX User Experience (Design)
WHO World Health Organisation
VR Virtual Reality
XR Extended Reality

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