POLITECNICO DI TORINO

Degree Course
Mechatronic Engineering

Master's Degree Theses

Improvement and Validation of a Spring-Based Pelvis Module for the Lokomat Exoskeleton: Control, Sensors, and Human-Robot Interaction.

A decoupled multidimensional conformal Lokomat pelvic support actuator

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Abstract

The main objective of this thesis is the study and design of a mechanical structure, in particular, a pelvic plate, capable of improving the interaction between the exoskeleton and the human being, validating the behavior of an exoskeleton used in rehabilitation.
I had the opportunity to work with the Lokomat, a wearable grounded treadmill gait device, located at the Technical University of Delft. The Lokomat is an exoskeleton that has been on the market for some time and is used for rehabilitation, especially for stroke patients. It is an innovative robot, compared to its competitors because it is more flexible and allows greater freedom of movement for the user, who is however assisted and guided during rehabilitation. Initially, the Lokomat system, the object of analysis in my thesis, did not involve a rigid connection to the pelvis, it was only connected to the user's legs. This led to a lack of synchronization between the user's pelvic movements and the exoskeleton's pelvic plate movements, leading to delays and inconsistencies in interaction between the robot and the user. Through a review of the literature, I tried to understand the existing solutions by analyzing the differences between the various exoskeletons that have rehabilitation as their common goal.
My research was aimed at developing a mechanical design solution that could fill this existing gap creating a connection support between the user and the pelvis plate to harmonize movements while guaranteeing perfect adherence and alignment.
This required careful evaluation of the existing system and identification of areas for improvement. The initial phase of my research focused on planning and implementing the new connection mechanism, with the ultimate goal of optimizing the coupling between the robot and the user's body, allowing the system to precisely track and replicate the user's movements without noticeable delays. The new design incorporated elements such as the C-shaped structure, providing greater stability and better alignment with the user.
To ensure the effectiveness of the design, testing and validation of the integrated sensors were conducted. This validation process aimed to verify the accuracy and reliability of the collected data and the overall functionality of the system. Furthermore, a pelvic controller was also studied and implemented along with the new C-shaped design. The experimental phase involved testing the effectiveness of both the pelvic controller and the new design in improving the transparency of the exoskeleton and its ability to better follow the user's movements. The experiments were conducted with human participants who performed walking tasks under various conditions, including the C-shaped design with the pelvic controller turned on and off. Participants were asked to perform normal walking movements while their interactions with the robot were monitored and recorded.
Our purpose was to evaluate the system's ability to accurately track participants' movements in real-time. Additionally, participants were asked to provide subjective feedback on their experience, including factors such as comfort, ease of use, and perceived responsiveness. The analysis aimed to evaluate the effectiveness of integrated planning in achieving the desired objectives: better tracking accuracy and better interaction human-robot.
By establishing a stronger and more efficient connection between the robot and the user, the Lokomat system is expected to provide better rehabilitation outcomes and improve the overall experience of those undergoing robot therapy.

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1 Introduction

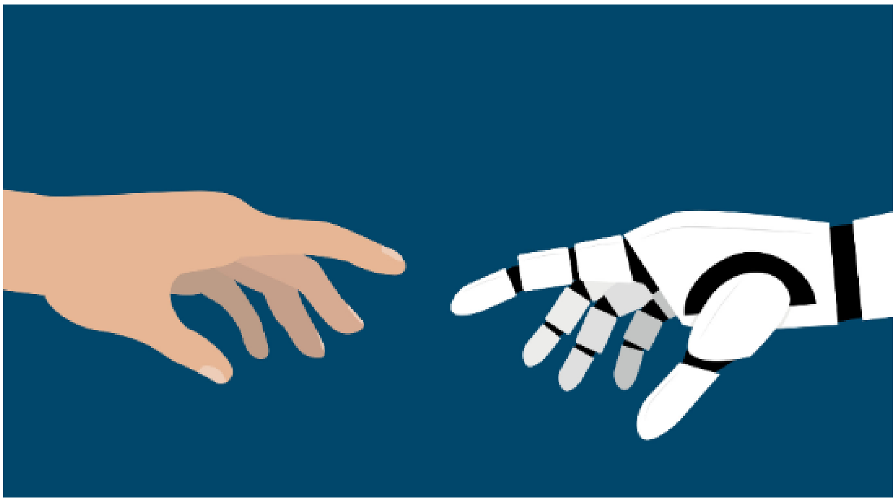


Figure 1: [37]

The ergonomic integration of humans with intelligent technological systems, which until some time ago was only used in the industrial or military field, is now increasingly prevalent in the medical field, especially in healthcare and rehabilitation techniques for individuals with disabilities.

According to the 2018 statistics from the World Health Organization (WHO)[1], more than one billion individuals, constituting 15% of the world's population, live with some form of disability. Over 190 million (equal to 3.8%) are individuals over the age of 15 who suffer from some form of limitation of motor functions and this number is constantly increasing.[37]

Accidents, injuries, aging, stroke, and neural diseases are the main causes of impaired motor functions.

Stroke, for example, which is the third most common cause of death is also the main cause of disability in adults especially in developed countries [1].In the United States, just over half a million cases of stroke occur each year [2].

Furthermore, the progressive lengthening of life expectancy (according to UN statistics, in 2050 there will be around *2.1 billion individuals over 60*) due to medical progress and the spread of healthcare facilities has also led to an increase in the rate of disability, a direct consequence of physiological changes due to aging, disabilities that almost certainly transform into mobility problems that tend to become chronic [3][4]. However, longer life expectancy must coincide with an improvement in the quality of life, it is therefore necessary to guarantee, what will represent a good part of the future population, a normal life, reducing to a minimum the inconveniences due to a reduction in mobility capabilities.[45]

However, regardless of whether the disability is due to disease or age, "every person should have the right to live a life without disability", [5],physiological function should be part of our human rights and as a society, we can achieve these rights if we accept the statement that humans are not disabled Rehabilitation must therefore include all those health measures aimed at avoiding or at least reducing the negative effects caused by diseases or accidents on functional abilities.
The rehabilitation intervention represents an education process for the restoration of functionality in order to reach the best level of possible health, understood by the World Health Organization as "a state of complete physical, mental and social well-being".[44] Through it, it will be possible to obtain socio-family, scholastic, and work reintegration. Starting from these considerations, robot-assisted rehabilitation is to be considered part of the rehabilitation intervention which aims to integrate standard rehabilitation treatments through the interaction between rehabilitation professional, patient, and robot [23].

2 Background and context

But what do we identify as an exoskeleton?

Examining the etymology of the word helps us understand what exoskeletons are. In biology, the prefix *"exo"* is derived from Greek, meaning outside, and *"skeletos"* means stand. *"Exoskeleton"* is therefore the expression used to describe the external structure, more or less rigid, which protects the body of some animals or insects and gives support to the internal organs.
As often happens in the technological field, reference is made to nature, and the term "exoskeleton" indicates those mechanical devices that can be worn outside the body, designed to increase man's muscular power, constituting a sort of "artificial musculature." They are also called "exosuits" or "exoskeletons" and have been used, above all, in the industry to facilitate particularly demanding jobs or in the military sector to increase the physical ability of soldiers, and nowadays also in the medical field, especially in rehabilitation for the re-education of motor skills.[31]

2.1 Chronology: Evolution of Exoskeletons

The first exoskeletons in history, with the sole function of protecting the human body, were the armors used in ancient times by the Greeks and Romans whose evolutions then led to the metal armor of medieval knights. They were armors made up in most cases of metal plates held together by leather straps whose main purpose was to protect the soldier during combat. [46] The first mention of the exoskeleton, in the modern meaning of the term, came with a patent by a Russian engineer, Nicholas Yagn, filed in 1890, whose invention called "Apparatus for facilitating walking, running and jumping" aimed to increase the ability to race of soldiers of the Russian army[6].
The system involved the use of springs mounted parallel to the legs, which allowed the weight of the body to be discharged to the ground and reduced the load of fatigue on the

lower limbs. The apparatus was powered by compressed gas contained in a wearable bag which the user placed on his shoulders Figure(2).

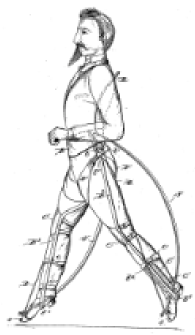


Figure 2: The exoskeleton of Yagn

A few years later, with a patent filed in 1917, Leslie C. Kelly completed his powered exoskeleton with a small steam engine and registered it under the name " Pedomotor.[7] Actually, there has never been any certain information on the actual realization of either Kelly's Pedomotor or Yagn's Apparatus.
To study the development of robotic exoskeletons we had to wait until 1966 when GE Research (USA) produced the exoskeleton called Hardiman (Figure 3), an enormous structure made up of enhanced arms and legs capable of producing a total force of one ton which it allowed the user to lift very heavy objects, but the reduced mobility of the body, stability problems and the demand for 45 kW of power did not allow its development, Hardiman was in fact produced in a single experimental model [8].

Figure 3: Hardiman exoskeleton [8]

Towards the end of the 1960s and the beginning of the 1970s at the University of Wisconsin-Madison, exoskeletons for walking assistance began to be developed, an activity also started at the Mihajlo Pupin Institute in Serbia. However, due to the limitations of the technical knowledge of the time and the lack of experience, it took several years before the ability to produce exoskeletons that could be placed on the market was developed.
At the end of the 20th century, the USA launched the EHPA (Exoskeleton for human performance augmentation) project to study exoskeletons in the military sector.
But it was at the beginning of the 21st century with the improvement of the performance of computers, actuators, and battery life that projects on exoskeletons increased, taking into consideration other areas besides the military one and in particular the rehabilitation and industrial one, with exoskeleton projects in various parts of the world such as USA, Japan, Korea, Great Britain, Germany and Italy. [9]

2.2 Classification of exoskeletons

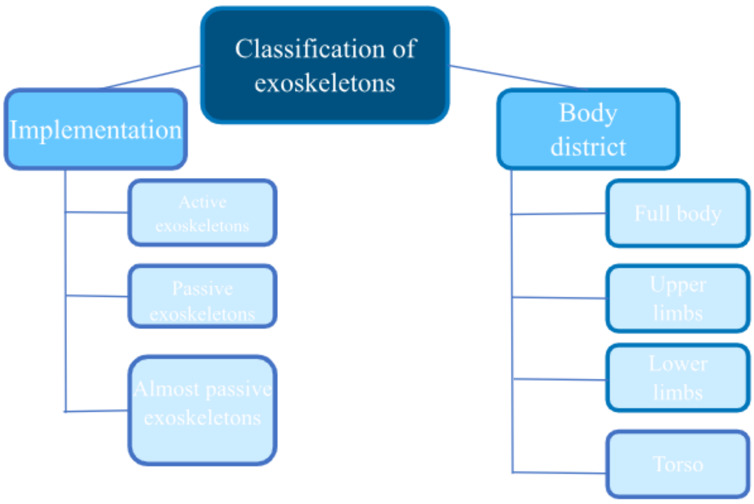


Figure 4: Classification of the exoskeleton[22]

The first main classification concerning the actuation system is to distinguish active exoskeletons from those defined as passive.
Generally speaking, an exoskeleton that is powered is defined **active**, is designed based on the morphology of the human body and uses one or more actuators to support or augment the capabilities of the individual wearing it. Actuators are those drive devices activated by electric motors or by hydraulic or pneumatic systems.
Through sensors appropriately positioned on the structure, data on the subject's movement intention are collected, these are processed by a regulator and sent to the actuators which carry out the appropriate movement of the exoskeleton and consequently of the

person. The types of actuators usually most used are electric motors, characterized by high efficiency and the possibility of adjustment via speed reducers according to need. Hydraulic actuators are also used but, due to possible fluid leaks and the complex management of the pipes, they actually have a small field of application. Using an active exoskeleton also implies a choice on how to power the device which can be done either via lithium batteries or by connecting it directly to an external energy source.
An exoskeleton is instead defined **passive** when it does not use actuators but usually springs or shock absorbers capable of accumulating energy during human movement and then using it to achieve or maintain a certain posture such as for example, trunk flexion[22].
An exoskeleton **almost passive**, instead, uses solutions such as proportional valves or final or actuated clutches which have passive characteristics, but require energy for their control [32].

With respect to the body areas supported by the exoskeleton, four macro areas can be distinguished:

- complete body that covers a large part of the entire body and are what are called enhanced exoskeletons
- Upper limbs are those that act on arms and require great flexibility
- lower limbs are those that affect the legs, which are very simple in their construction but require particular requirements of strength, stability, and mobility
- and trunk which carry out trunk support operations during flexion or extension operations.

In some exoskeleton models, there is the possibility of supporting multiple parts of the body at the same time depending on the intended use.
Finally, concerning the area of use, three categories can be distinguished:

- military field, used to increase the capabilities of soldiers or to assist them in dangerous environments
- industrial field used to increase productivity and improve the working conditions of operators
- medical field and are exoskeletons aimed at patients who need rehabilitation

As mentioned previously, there are many fields in which exoskeletons are used.
In this work, only exoskeletons used in the medical field for rehabilitation purposes were taken into consideration.[22]

In the field of medical rehabilitation, we can divide exoskeletons for upper limbs or for lower limbs, about the part of the body for which they are used, and into wearable terminal effectors or grounded terminal effectors, as illustrated in the following Figure(5) [10].

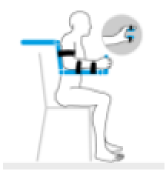
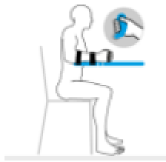
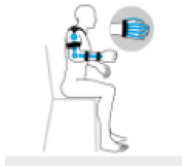
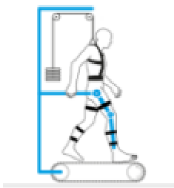
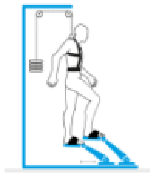
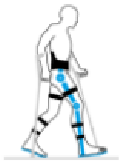
	Wearable	Final effector connected to earth	To the ground
Upper end			
Lower end			
	Mechanical structure whose joints and connections are compatible with the limbs of human beings.	Achieve higher motion dynamics and enable rendering of a wider range of impedances	Stationary robots used in the medical field, typically in combination with other tools, such as computers and treadmills.

Figure 5: Schematic representation and classification of rehabilitation robots. Besides the extremity that is trained, rehabilitation robots can be broadly classified into grounded exoskeletons, end-effector devices and wearable exoskeletons. While the first two are well established, the latter are currently entering clinical application [10]

In 1997, with the publication of the results of the clinical study of a planar robot called Mit-Manus, used for the rehabilitation of the upper limb, it can be said that robot-assisted motor rehabilitation began. This study demonstrated that patients undergoing rehabilitation due to stroke experienced greater functional recovery with robotic assistance in addition to traditional therapy by physiotherapists.[17]
This does not mean that robot assistance is absolutely the only indispensable way to recovery, but what is certain is that the support they give in the repetitive movements of the limbs in rehabilitation and the possibility of active participation of the user does not shorten recovery times [18].
Studies on animal models have defined that several hundred repetitions of the same gesture are necessary to induce neuronal plasticity phenomena [19].
Since then, a lot of similar projects and studies have followed.

Lokomat

In 1999, the 4-DoFs Lokomat robotic orthosis was used on a patient for the first time[41]. The entire system consists of a treadmill, a body weight support system, two PCs, and the Lokomat itself. One PC handles the control task, the other serves as the graphical interface. This robot moves only in the sagittal plane and has four rotation joints (two per leg at the hip and knee) driven by four linear drives, containing force sensors, and a parallelogram structure, which allows vertical movement of the patient.
The actual hip/knee joint angles are measured by precision potentiometers and calculated by the PD position controller to achieve the reference hip and knee joint angles. The system uses a control algorithm based on inverse dynamics, controlling the impedance to obtain the desired torque on the joints.[40]

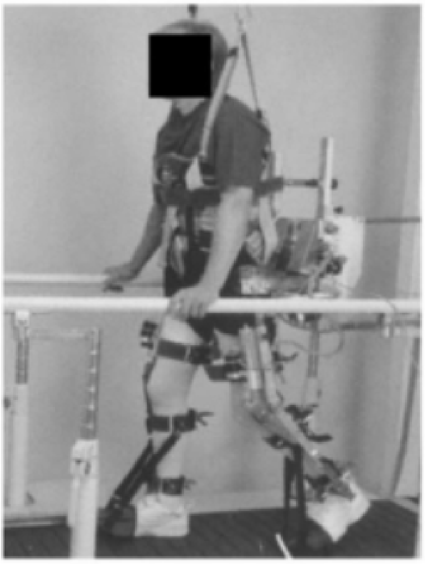


Figure 6: Automated Treadmill Training with Lokomat [41]

Lopes

Another important treadmill-based lower limb rehabilitation robot was presented in 2007.[12] It is called LOPES Figure(6) and combines a 2D activated pelvic segment, free to translate in all three axes, and a leg EXO containing three joints rotators in each leg, two on the hip and one in the knee. It is programmed to work in two ways: following patients or guiding them. The LOPES is electrically driven by servomotors and the control variable adopted is impedance as in the case of the Lokomat. Power is transmitted via

SEAs driven by a flexible Bowden cable transmission.[40]

Figure 7: a) Prototype of Lopes [12]

ALEX

The exoskeleton of the active leg ALEX Figure(7) [13] is a lower limb robot for walking assistance, developed for stroke patients. Some links, such as thigh or shank ones, are telescopic, to be able to adapt to different users. The EXO has a total of seven DoFs: three DoFs on the trunk (two translations and one rotation), two DoFs on the thigh (rotations in the sagittal and coronal planes), one DoF on the shank, and one DoF on the ankle. Movement of the hip and knee joint in the sagittal plane is powered by linear actuators, capable of generating up to 60 Nm, with integrated encoders to determine the current position. All other DoFs are held passively by springs. To apply normal and tangential forces to the user's ankle, a force field controller was developed.[40]

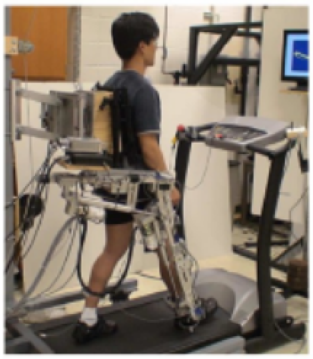


Figure 8: ALEX [13]

Obviously, these represent only a part of exoskeleton models developed in recent times and gradually introduced on the market. Assisted ortho-robotic therapy has led to good results, but it cannot yet be said that it has made a decisive leap in quality compared to traditional therapy, due to a limited experimental sample and the specific rehabilitation technique.[47] For these reasons, manufacturers have begun to promote their systems to demonstrate not only the capabilities of exoskeletons but also to raise awareness of the use of such systems to a wider audience. In an attempt to reduce the constraints caused by the size, weight, and rigidity of the exoskeleton structure but also to limit its costs, the concept of "exosuit" is beginning to emerge: soft robotic devices that can be worn like a dress. They provide support through cables integrated into the tissues or through soft actuators located at the joints. [48]

2.3 Lokomat innovations:

LOKOMAT

To revisit the subject of study in this thesis, I provide below a general overview of the evolution of the Lokomat which I have already defined, in the previous paragraph, a brief indication of its components and its use. Here I summarize the essential elements that constitute its structure. The Lokomat exoskeleton, produced by Hocoma in Switzerland, is a robotic device for the lower limbs designed for gait training in the rehabilitation of patients with impaired motor functions.
The version used for the study process of this thesis is a modified version (developed at ETH, Zurich, Switzerland) compared to the commercial version used in hospitals and rehabilitation centers around the world. The robotic device in question consists of three main modules: treadmill (TRM), body weight support (BWS), and pelvic module (MUCDA), as shown in Figure(9).

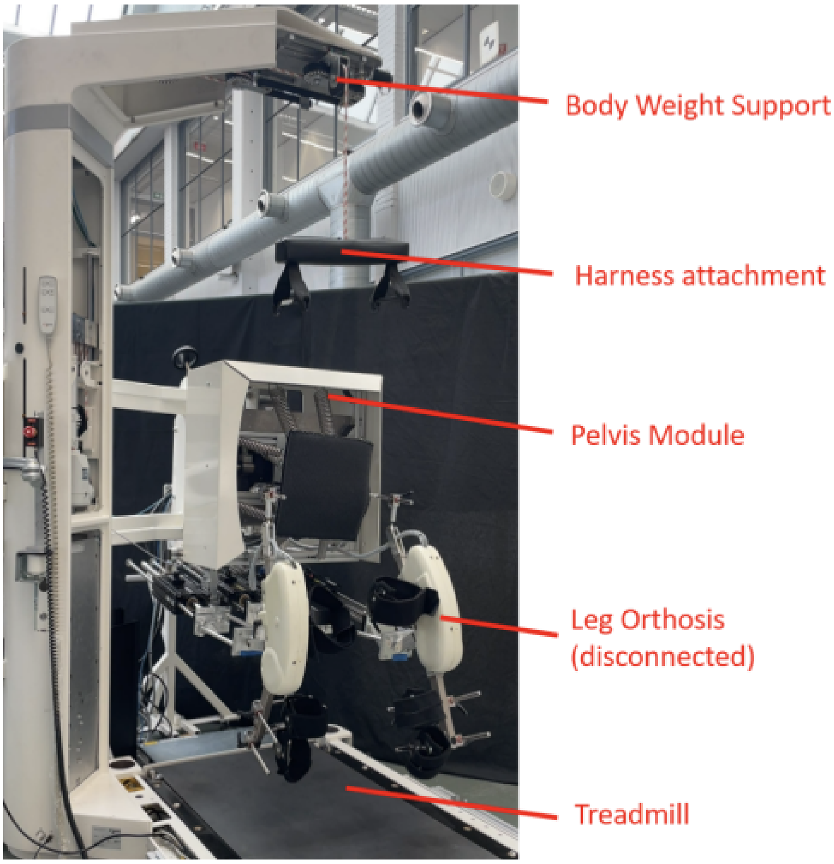


Figure 9: Lokomat device

Treadmill (TRM)

The treadmill is an integral part of the overall system, providing a controlled walking surface and user interface (see Treadmill in Figure(9)). The operator controls and adjusts the walking speed through a graphical interface operating in MATLAB/Simulink. The treadmill module is equipped with different levels of security, both software and hardware. Additionally, both the user and operator can use a remote button to immediately stop the treadmill in the event of an emergency.

Body Weight Support (BWS))

The Body Weight Support System (BWS), uses a pulley mechanism that can be adjusted based on the actual body weight the user must support while walking. To ensure a secure fit, the BWS is connected with a harness that connects the user to the overhead cable system (see Body Weight Support in Figure (9)). This system helps support the user's body weight maintain an upright posture while walking and ensure safety in the event of a fall. By adjusting the cable tension, users can experience controlled weight reduction

during rehabilitation exercises. The harness is adjustable and customizable to ensure a secure and comfortable fit. The operator can adjust the height and strength of the body weight support with a remote control.
The BWS is equipped with an electric motor that can move the pulley along the lateral direction. The lateral position of the BWS is controlled through a position control loop implemented in the Simulink model. The BWS is equipped with an incremental encoder and an absolute potentiometer that measures the lateral position of the pulley.

Pelvic module (MUCDA)

The Multidimensional Decoupled Actuator (MUCDA) was built and evaluated to interact with the human pelvis in six DoFs (see the pelvis module in Figure(9). The system, shown in Figure(10), is designed to actively guide the human pelvis to support lateral weight shift during treadmill walking, providing only minimal passive support to the remaining DoF of the pelvis. The MUCDA is equipped with an infrared camera and an inertial measurement unit (IMU) to measure the relative displacement of the front plate relative to the center plate. Furthermore, the MUCDA is equipped with a linear actuator to move the intermediate plate laterally relative to the fixed plate. The linear actuator control logic is implemented in the Simulink model. Different control strategies can be used, such as transparent control, position control, or force control.

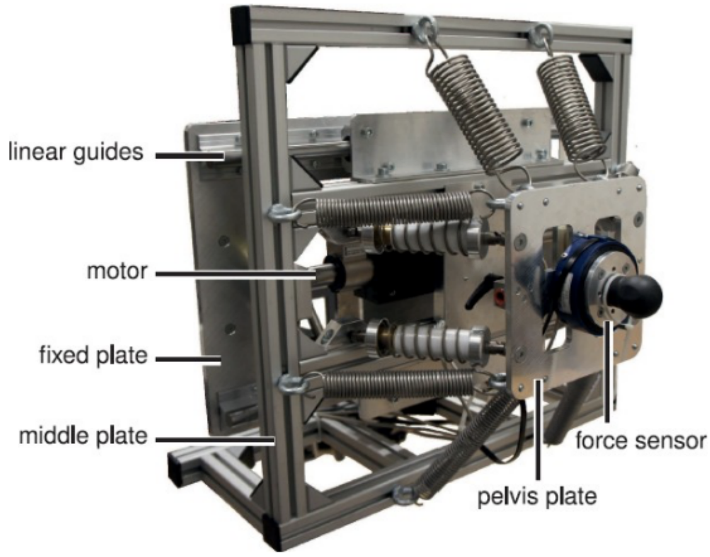


Figure 10: The compliant basin module (MUCDA) is driven by a linear motor. The force sensor is installed for evaluation purposes only. [30]

Finally, there are also optional devices as building blocks of the modified Lokomat, such as head-mounted displays (HTC, Varjo, etc.) and the VR tracker (HTC) motion capture system (OptiTrack). Head-mounted displays can be used in conjunction with the exoskeleton to provide visual feedback to the user while walking. VR trackers and motion capture systems can be used to track the position and orientation of the user's limbs and torso while walking.
Concretely, the device is connected to the user's pelvis via a harness which in turn is connected to the body weight support (BWS) and the pelvic module (MUCDA).
The harness covers the lower half of the torso and wraps around the inside of the thighs, resembling a climbing harness. The patient walks on the treadmill (TRM) and the safe body weight support relieves the burden. It should be noted that the device can also support lateral movements driven by both the BWS and the MUCDA.
The device is controlled via a Simulink Real-Time model that reads the sensor system and provides control signals to the system's actuators.
The Simulink Real-Time model is implemented in two Target xPC machines, one for the treadmill and one for BWS and MUCDA.
When interacting with humans it is important that robots are as transparent as possible, so as not to interfere with natural movements. For rehabilitation purposes, it is important that the patient feels supported and safe but at the same time feels free so that he can also make mistakes to recover lost functions more quickly. The robotic structure is always in contact with the user's limb and the axes of the joints are aligned with the anatomical ones of the user. [30]
Simple and functional solutions are needed to reduce weight and bulk but maintain different degrees of mobility.

A much-pursued solution is sub-actuation, i.e. a system in which the number of actuators is lower than the number of joints. This reduces weight but not joint mobility. The sub-implementation must interface for motion distribution, in a mode mediated by torque sensors arranged in an antagonistic manner connected to a fixed base. While this allows free movement in five of the six DoFs, such a mechanism does not allow the applied forces to be perfectly lateral. Instead, force components may need to occur in other directions. This can be avoided by connecting the limbs not to a fixed base, but rather to mobile points that passively follow the main movements of the pelvis, in particular the antero-posterior movement [38] although even this still does not guarantee complete decoupling of the DoF.[30]
The innovation lies precisely in the design of the pelvis module which allows the natural movement of the pelvis, thanks to the use of SEAs. The Series Elastic Actuator (SEA) is an important example of using physical compliance to improve force control. Its main feature is an elastic element in series with a rigid actuator [20].

In the following Figure(11), I have listed the differences and similarities of rehabilitation robots that share similar purposes to the Lokomat, for the purpose of comparing current existing solutions.

Traidmil Gait Trainers

Exoskeleton-based systems use a treadmill with a robotic exoskeleton connected to the patient's legs to guide and control lower-limb joints directly.

	Description	Dressing Time	Motion allowed	DOF	BWS	Control
Lokomat/ Reoambulator	robotic gait orthosis advanced that uses computer controlled motors (drives)	15/20 min	Restrict movement to the sagittal plane only.	4 DOF	body-weight-supported treadmill robotic system	Impedance controller
LOPES	It can move in parallel with the legs of a person walking on a treadmill, at pelvis height flexibly connected to the fixed world	20 min	it is able to move not only on the sagittal plane but its movements are limited	6 DOF	body-weight-supported treadmill robotic system	Impedance controller
PAM	pneumatic gait training robot that allows for a full range of natural motion of the legs and pelvis during treadmill walking, and provides compliant assistance	20 min	This design allows unconstrained range-of-motion of the pelvis during normal gait, and provides room for arm swing and an unobstructed field-of-view for the individual	5 actuated DOF	body-weight-supported treadmill robotic system	Admittance controller

Figure 11: Differences and similarities of rehabilitation robots

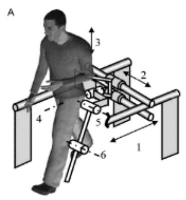
The pelvis is often locked in the horizontal plane but must prevent the weight from shifting from the right leg to the left, but balance training is a fundamental goal of rehabilitation.[36]
The Pelvis module is designed and evaluated to accurately track and represent interaction forces between humans and robots and provide a safe yet transparent environment.
The innovation lies in using SEA for physical compliance to improve force control. The

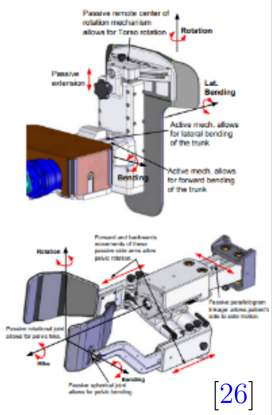
concept turns force control into a position control task because the deflection of the spring element serves as an indirect measure of force.

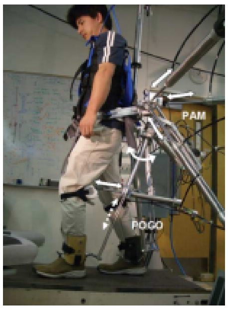
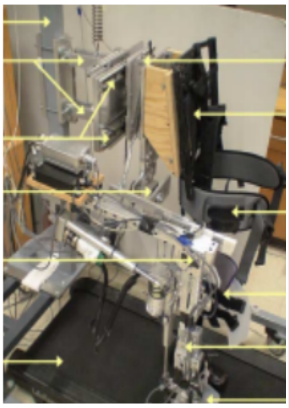
The combination of passive compliance and the SEA concept leads to high transparency in all six DoFs, which should encourage a higher degree of active participation and thus more positive outcomes in gait training.
This is the big difference between the old Lokomat and all the other robots and the new Lokomat.
[30] For rehabilitation purposes, it is important that there are more degrees of freedom, such as the possibility of being able to move the weight from one leg to the other and this is only possible thanks to the movement which can also be allowed on the front of the plane [36]. The innovation therefore lies in the fact that this robot is more flexible, leaving more freedom of movement to the user who is still assisted and accompanied during rehabilitation.
Despite the innovation of the custom robot, I identified necessary improvements.
Freedom of movement is given thanks to the SEA with which the MUCDA was designed which certainly makes the lokomat more transparent but on the other hand, there is still no connection between the pelvis plate and the user and this makes it a bit useless innovation such as the plate must be able to perfectly follow the user's movements.[30]

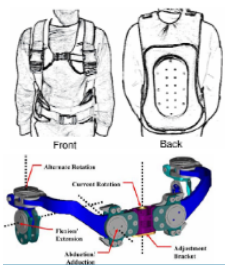
Before designing support capable of guaranteeing the one just described, I looked and researched the literature to understand if there were solutions that already answered this question.

Table 1: Summary Table.

Robot	Representation	DOF	Connection
LOPES: LOPES allows translations of the pelvis on the horizontal plane and abduction/adduction of the hip. These additional DoFs can be useful for training as they allow tasks related to balance control to be left to the patient. The importance of adding pelvic movements to gait training. [24]	[24] *(a) DOF of the pelvis and leg segments of the LOPES gait rehabilitation robot*  (1) forward linear guide, (2) sideways linear guide, (3) parallelogram for vertical motion, (4) hip frontal rotation, (5) hip sagittal rotation, and (6) knee sagittal rotation. The two horizontal motions (1) and (2) and the hip frontal rotation (6) are optionally blocked in the experiments. Except for (3) are all mentioned DOFs actuated. (A) indicated the height adjustability of the support frame.	The horizontal movements of the pelvis (1 and 2) are activated. The vertical movement of the pelvis is not implemented.	The LOPES exoskeleton is connected to the fixed world, at the height of the pelvis. This allows you to compensate for the weight of LOPES and apply external corrective joint forces or torques to the patient's pelvis

LOPES II:	*(a) Patient is connected to LOPES II with a harness, clamps just below the knees, and foot brackets .*  Force sensors (1) are located closely to the patient, and the spherical gimbal at the pelvis (2) allows for rotations of the pelvis [25]	Hip flexion/extension, hip abduction/adduction the forward/backward pelvis and mediolateral pelvis are motorized. All other degrees of freedom can be left free and the frontal and transverse rotation of the pelvis can be constrained. DoF Pelvis anterior/posterior Pelvis mediolateral Pelvis up / down Pelvis sagittal rotation Pelvis frontal rotation Pelvis transversal rotation Hip abduction / adduction Hip flexion / extension Hip endorotation / exorotation	To minimize the moving mass of the robot, a fixed system was incorporated in LOPES II. We used a push-pull rod structure, to transfer motor torques to the patient, since they are light and stiff, to apply forces on the hip joints and allow pelvic rotations in all three directions. The patient is suspended from a harness connected to a pneumatic body weight support system (BWS).
KineAssist Mobile base and intelligent brace. THEthe trunk support attaches to the patient at chest level via the harnesses. In addition, the trunk support can bear some of the load related to the body weight support operating mode. The pelvis support mechanism is used as a stabilizer, body weight support system and as a safety mechanism for the prevention of vertical falls.	*(b) (upper) Detail of trunk control mechanism. (lower) Detail of pelvis control mechanism.*  [26]	The center's remote passive rotation mechanism allows for torso rotation. The active mechanism allows lateral flexion of the trunk. The active mechanism allows forward flexion of the trunk. The back and forth movements of these passive lateral arms allow for pelvic rotation. Passive connection of the parallelogram: allows lateral movement of the patient. The passive ball joint allows for pelvic flexion. The passive rotational joint allows for pelvic excursion and allows the person to bend movements both left/right, forward/backward,	Pelvic and torso harnesses serve as the interface between the machine and the patient and provide the means to comfortably apply desired forces to the body, as well as acting as a fall arrest device. The harness is designed in two pieces, the upper level harness to secure the torso and the lower level harness to secure the pelvis. The two-piece design further simplifies sling management issues that arise when securing the patient. [26]

PAM and POGO: PAM can assist in 5 DoF of pelvic motion, while POGO can assist in hip and knee flexion/extension.	*(a) PAM, POGO*  [27]	The resulting system has five DOFs, providing control of three translations (lateral, forward and backward, up and down) and two rotations (pelvic rotation around the Z-axis and pelvic obliquity around the Y-axis). . One rotation cannot be controlled: the pelvic tilt around the X axis.	Two three-degree-of-freedom pneumatic robots are mounted on adjustable pillars and attached to the end of a belt worn by the subject. The BWS mechanism partially relieves the patient's weight depending on the desired level of support. [27]
ALEX: A walker equipped with a torso harness keeps the person stably on the treadmill during exercise.	*(b) Powered leg orthosis, its major components and all the DOFs are labeled.*[28] 	The trunk of the orthosis, which is connected to a walker and has three DOFs: vertical and lateral translations and rotation around the vertical axis and around an axis perpendicular to the sagittal plane. The hip joint in the sagittal plane is activated. All other degrees of freedom are passively maintained with springs.	The connection between the user and the exoskeleton is rigid. The U-connections end in tears. [28]

BLEEX Pseudo-anthropomorphic, has hip, knee and ankle joints like a human.	*(a) BLEEX Hip Degrees of Freedom (viewed from back).*  Although both the abduction/adduction and flexion/extension axes pass through the center of the human hip joint, the rotation axis does not. The adjustment bracket, between the two abduction/adduction axes, is replaceable to accommodate wearers of various widths. [29]	3 degrees of freedom at the hip	The BLEEX torso connects to the hip structure. The front torso is equipped with a harness worn by the operator. This harness is the second rigid attachment point for the operator. Typically, the harness consists of a curved, rigid back plate that attaches to the torso and includes comfortable backpack-like straps that grip the operator and distribute forces across the torso, chest, shoulders, and upper back of the operator. Various harnesses have been created to ensure maximum comfort for the operator. The exoskeleton harness must distribute forces and moments in any direction. In theory, only balancing loads need to be transferred between the operator and the machine, but during the development of the controller, the harness must support any load possible. [29]

From the conclusion of this literature review, the significant evolution of exoskeletons in the context of assisted rehabilitation clearly emerges.
Analysis of the innovations introduced by the Lokomat highlighted its ability to provide greater freedom of movement compared to its predecessors. However, the critical challenge of resolving user-pelvic plate interaction issues remains a significant barrier, highlighting the need for further research and improvements. While various solutions have been identified to address this challenge, gaps and limitations in current implementations have also been highlighted. These considerations provided a valuable context for the next phase of my investigation, aimed precisely at bridging current disparities and further advancing rehabilitation exoskeleton technology.
In this fundamental context, I have identified specific research objectives, to develop innovative solutions and significantly improving the interaction between the user and the pelvic plate within the Lokomat.

3 Research objectives

In this chapter, I outline the specific objectives that guided my research. Objectives are essential to clearly define what I wanted to achieve with this study and to ensure that the research was conducted in a structured and effective way. The work began with an in-depth study of the various models of rehabilitation exoskeletons to frame the problem and understand the characteristics of the design activity of the mechanical structure, and the related accessory components necessary for its functioning, to pursue the implementation of this mechanical structure that would improve its use and functioning.

3.1 Introduction to the research

In this section, I set out the fundamental objectives of this research, contextualizing it within the overall narrative of innovation and improvement in the field of exoskeleton-assisted rehabilitation.
In exploring the landscape of exoskeleton technology it is evident that rehabilitation devices such as the Lokomat have significantly improved the recovery potential of patients. But as always happens, with innovation comes the imperative for improvement. The Lokomat's unique feature of allowing greater freedom of movement than its counterparts is a promising step forward. However, a critical challenge remains: creating a perfect connection between the user and the exoskeleton's pelvic plate.
This research addresses this crucial challenge by developing a mechanical design solution to bridge the gap. The goal is to create a connection support mechanism that harmonizes the user's movements with the pelvic plate, ensuring perfect fit and alignment. Through an extensive review of relevant literature, we discovered the different solutions and disparities between exoskeletons designed for rehabilitation.
This study is preparatory to the detailed exposition of the specific research objectives and provides a clear and convincing motivation for my work. It highlights the importance of

the research mission and the urgent need to integrate innovative solutions in exoskeleton-assisted rehabilitation.

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3.2 Specific objectives

As already mentioned previously, as a part of this research, I established a series of specific objectives to pursue, each tailored to address a crucial aspect of the exoskeleton-assisted rehabilitation system. These goals represent the roadmap to ultimately achieve a better and more responsive interaction between users and the Lokomat exoskeleton.
My research objectives include:

- mechanical progress
- sensors integration
- controller optimization

all factors that contribute to my ultimate vision of a more effective and user-friendly rehabilitation experience. Each of the specific objectives remains closely linked to the mission of improving the interaction between exoskeletons and their users.

3.2.1 Mechanical Objectives

My first activity aimed at achieving the set objectives focused on the mechanical aspects of the Lokomat system which include the design and implementation of a connection mechanism between the user and the pelvic plate. Achievement of these specific mechanical objectives has included:

1. **The Mechanical design**
   The Mechanical design of a mechanism that guaranteed a rigid and continuous connection between the user and the pelvic plate of the Lokomat in such a way as to optimize the coupling system and alignment during rehabilitation sessions and evaluate the level of comfort and satisfaction. Mechanical design represented the fulcrum of my research which started from the study of the design and the creation of prototypes capable of empirically testing the feasibility and effectiveness of the mechanism.

2. **Comfort and user experience**
   User comfort and experience are paramount in the context of rehabilitation. To this end, it was necessary to ensure that the designed connection support ensured comfort for users by integrating padding and hypoallergenic materials that prevented

discomfort or skin irritation during prolonged rehabilitation sessions. I therefore tried to design a non-invasive yet ergonomic solution that would allow users the freedom to move naturally during rehabilitation, without impeding movement or compromising comfort.

3. **The integration of connection support** to bridge the gap between the Lokomat's pelvic plate and the user's body. Creating a robust and adaptable interface that ensured a rigid connection while accommodating various body shapes was not enough. A connection support system needed to be designed that not only seamlessly connected the pelvic plate to the user but also allowed precise tracking of movements in multiple planes, including sagittal and frontal. The design needed to offer adaptability while accommodating a wide range of user sizes and therefore ensuring inclusivity for a broad user population.

4. **Transparency and rigidity**
   Transparency and rigidity are key attributes to improve the performance of the Lokomat. My goals in this regard have been to develop a connection support mechanism that does not compromise the transparency of the exoskeleton, the robots must not hinder or limit mobility, but only operate for the required tasks guaranteeing full freedom of movement for the user and precise effectiveness of the rehabilitation process, by creating a connection support system that maintains a rigid connection between the pelvic plate and the user, allowing precise monitoring of the user's movements and minimizing delays. Through these specific mechanical objectives, my research endeavored to address the mechanical challenges posed by the Lokomat system, with the ultimate goal of improving its functionality, comfort, and adaptability.

3.2.2 Sensor interaction

In the field of sensor validation and integration, my research was aimed at trying to achieve those objectives aimed at ascertaining the precision and reliability of the data collected by the Lokomat's integrated sensors. I carried out this analysis through a validation experiment of the sensor dedicated to movements controlled by the Lokomat pelvic plate. Sensor validation is critical to ensuring the accuracy of the data collected during the operation of the Lokomat. In this context, the experiment is dedicated to the validation of the sensor, from which the controlled movements of the pelvic plate of the Lokomat derive, the objective is to validate the measurements of the data provided by the infrared camera by testing its precision and calculating as relative error to the ground truth(Optitrack). Validating infrared camera measurements leads to understanding whether the use of an additional Kalman filter improves accuracy.
This comparative analysis aims to evaluate the consistency and accuracy of the data generated by the Lokomat system sensors. Through these sensor analyses, my research strives to ascertain the integrity and reliability of sensor data, ensuring their suitability for subsequent experiments and analyses.
This validation process is essential to support the credibility and robustness of the data collected during Lokomat operations, consequently improving the accuracy of research

findings.

3.2.3 Controller Optimization

The pelvic component of the Lokomat implements a controller specifically designed for the MUCDA system. To optimize the controller's activity, a dedicated control algorithm was created for the MUCDA. The controller can facilitate seamless interaction between the human pelvis and the Lokomat, ensuring synchronized movements in all six degrees of freedom (6 DOF).
It was therefore crucial to establish a control structure that would detect any displacement or misalignment between the front and center plates of the Lokomat.
When such a shift occurs, the controller should autonomously generate and apply corrective forces to realign the plates, allowing them to move in unison. This feature ensures that the movements of the front plate are faithfully replicated by the central plate, ensuring precise and synchronized tracking of the movements of the pelvis. Pursuing these controller goals, my research sought to advance the Lokomat's capabilities in providing synchronized and transparent support for pelvic motion during rehabilitation.
This controller implementation is critical to improving the utility and effectiveness of the Lokomat in assisting users during therapy sessions.

3.3 Motivation

The motivational drive behind the efforts of this study is based on the search for excellence in the field of exoskeleton-assisted rehabilitation, with particular attention obviously to the Lokomat system. This section delves into the main motivations and justifications of the chosen research objectives.
The Lokomat, as I have already said previously, represents a notable advance in rehabilitation technology for walking training. The system is designed in such a way as to allow you to modify the walking parameters (speed, stride length, knee joints, and of the hip) throughout the entire rehabilitation period, plus the system interacts with the patient, who actively participates thanks to virtual reality visible on the screen. We therefore understand the importance of highlighting an effective connection between the user and the pelvic plate of the Lokomat, which I remember represents the fulcrum of my entire research experience, an essential connection to ensure that the exoskeleton accurately follows and supports the user's movements, providing optimal rehabilitation results.
The logic of our research can be summarized in several key points: *Improve user experience*: We recognize that the success of rehabilitation therapy depends significantly on patient comfort and experience. By improving the connection between the user and the Lokomat pelvic plate, we aim to create a more comfortable and user-friendly rehabilitation environment. This, in turn, may encourage greater patient compliance and adherence to treatment regimens.

Optimize rehabilitation outcomes: the effectiveness of rehabilitation therapy depends on the precise detection of the user's movements. This research aims to ensure that Lokomat can perfectly replicate the user's pelvic movements, leading to more accurate therapy sessions and potentially faster recovery times.

Expand user inclusivity: rehabilitation therapy should address individuals of different body shapes and sizes. The set goals include designing a connection support mechanism that can adapt to a wide range of user profiles. This inclusiveness ensures that a wider population can benefit from exoskeleton-assisted rehabilitation.

Maintain transparency and rigidity: the transparency and rigidity of the exoskeletal system are essential for both user comfort and therapy effectiveness. My goal was to find a balance between these factors, allowing the user to move naturally while maintaining a rigid connection for precise tracking and support.

Validate sensor data: The accuracy and reliability of sensor data are critical to ensuring research success. The rationale behind the sensor validation objectives lies in the need to affirm the credibility of the data collected during Lokomat operations, supporting the accuracy of the research results.

Improve the controller: the main function of the controller is to provide the Lokomat with the ability to autonomously detect and correct movements between the front and central plates. This feature ensures that the user can experience synchronized and faithful support of the movement of the pelvis during therapy.

My research is driven by a commitment to improving the rehabilitation experience of patients using the Lokomat system. By addressing the issues related to mechanical design, sensors, and controller implementation, which lead to giving small impulses to the progress of exoskeleton-assisted therapy, ultimately the quality of life of people forced to undergo rehabilitation is also improved.

3.4 Motivation and methodology

In this section, I have described the rationale behind my research objectives and the methodologies used to achieve them. I have outlined the practical strategies and approaches that have supported this quest to innovate and improve exoskeleton-assisted rehabilitation. The methodological stages were in practice the following:

1. identification of the problem
2. search for similarities and differences in pre-existing literature
3. critical reading of existing studies
4. design and mechanical design
5. Sensor validation
6. Controller implementation
7. verification and writing of the result

3.4.1 Mechanical design logic and methodology

Connection support mechanism: My rationale for improving the connection support mechanism comes from the recognition that an effective mechanical connection between the user and the Lokomat pelvic plate is critical to the success of rehabilitation therapy. I addressed this challenge through a methodology based on iterative design and prototyping. I used Solidworks to design and 3D printing technology to create and test connection support solutions. The prototypes underwent evaluation, including connection stiffness tests and user feedback. The objective always remained to maintain the transparency and rigidity of the Lokomat system.

Comfort and Ergonomics: It is a commitment to the user comfort and ergonomic design is reflected in the methodology adopted. It is necessary to think about healthcare patients to collect information on the most comfortable materials and padding. These insights informed the selection of hypoallergenic materials and the design of ergonomic, non-invasive solutions. User trials and feedback sessions play a central role in this iterative process.

3.4.2 Sensor validation logic and methodology

Validation experiment: Validation of sensor data is based on the fundamental importance of accurate data in evaluating rehabilitation outcomes. The methodology involved a complete sensor validation experiment. Controlled movements were applied to the pelvic plate of the Lokomat, generating data for comparative analysis. I used sensor techniques analysis to validate the accuracy and consistency of the sensor data.
This methodology involves the use of the truth measurements obtained through optitrack

technology.
Precision of the infrared camera: To evaluate the accuracy of the infrared camera measurements, I applied relative error analysis by comparing the sensor data with the ground truth. This methodology ensures that the data collected by the Lokomat system is reliable and suitable for subsequent experiments and analyses. Additionally, we explore the potential benefits of incorporating a Kalman filter to improve data accuracy.

3.4.3 Controller improvement logic and methodology

Synchronization and control: The rationale for implementing a pelvic plate controller is to achieve synchronization between the frontal and central plates. My methodology focused on the development and implementation of control algorithms based on real-time sensor feedback. I used control theory and computational modeling to create algorithms that can detect and correct plate shifts. The methodology involved tests and simulations to refine and optimize these control algorithms.

Experimental validation: to validate the effectiveness of the controller it is necessary to conduct experiments. These experiments compare the performance of the Lokomat with and without the controller activated. Data on plate movements is collected in real-time. The methodology included statistical analyses to evaluate the impact of the controller on synchronization.

The rationale behind my research objectives is supported by a solid and comprehensive methodology. This methodology includes iterative design processes, sensor validation experiments, and real-time control algorithm development. It highlights our commitment to providing tangible improvements in exoskeleton-assisted rehabilitation and ensuring the reliability and effectiveness of our research findings.

3.5 Importance of the project

In this section, I bring together the rationale behind this research objective and the broader meaning of the project. I shed light on the profound impact that work can have in the field of exoskeleton-assisted rehabilitation, highlighting the transformative potential inherent in the objectives set.

3.5.1 Summary of objectives:

The research objectives, as outlined in Section 3.2, constitute the pillars on which this project is built. These specific objectives, classified into mechanical, sensor-related, and control aspects, provide a clear road map to achieve the overall mission: improving the interaction between exoskeletons and their users in the context of rehabilitation.

Mechanical objectives: The pursuit of mechanical excellence, as described in Section 3.2.1, is driven by the need to create an effective connection support mechanism. This mechanism, characterized by seamless integration, user comfort, transparency, and rigidity, seeks to bridge the gap between the Lokomat's pelvic plate and the user.

Sensors objectives: Goals related to sensor validation and integration, as detailed in Section 3.2.2, mean commitment to precision and reliability. Through validation experiments, we guarantee the integrity of sensor data, the cornerstone of my research. The accuracy of these data, verified through comparative analyses, lays the foundation for informed decision-making in rehabilitation strategies.

Controller objectives: The development and implementation of a controller, discussed in Section 3.2.3, is in line with our goal of achieving synchronization and control. We strive to minimize plate displacement, improving the user experience during rehabilitation.

3.4.2 The meaning of the project:

The project has profound significance in the field of exoskeleton-assisted rehabilitation, offering a multifaceted impact:

1. Advancing rehabilitation technology: Addressing the crucial challenges of connection support, sensor data accuracy, and synchronization, contributes to the advancement of rehabilitation technology.
   We are in a new era where exoskeletons deliver improved user experiences and more effective therapeutic outcomes.

2. Improved user comfort and compliance: The emphasis on user comfort and adaptability in our mechanical goals speaks to the heart of patient care. The work aims to make rehabilitation sessions more comfortable and accommodating, thus increasing patient compliance and engagement.

3. Data-driven rehabilitation: Through sensor validation and control algorithm development, we give healthcare providers precise, data-driven information. These insights enable tailored rehabilitation programs that adapt to the needs of the individual patient, ultimately improving the efficiency and effectiveness of therapy.

4. Inclusivity and accessibility: My commitment to adaptability and inclusiveness in mechanical design ensures that a broad spectrum of users can benefit from exoskeleton-assisted rehabilitation. This makes this project instrumental in expanding accessibility to rehabilitation technology.

5. Research Advances: Beyond its immediate impact, it contributes to the larger body of research in robotics, control theory, and rehabilitation science. The methodologies and results can serve as valuable references for future research efforts. The research project is supported by well-defined objectives and has immense significance for the field of exoskeleton-assisted rehabilitation. It embodies the spirit of innovation, user-centered design, and scientific rigor, with the potential to reshape the landscape of rehabilitation technology and improve the lives of countless individuals on their journey to recovery.

4 Methodology

4.1 Mechanical Design

When analyzing the different exoskeletons used for rehabilitation, I noticed that, unlike the Lokomat, most of them had a connection at the pelvis level between the robot and the user. The first thing I investigated was to try to understand if it made sense to come up with a design that could allow this connection.
The lokomat is connected to the human via tears at the knee which ensure connection only to the legs.
However, to be as compliant as possible and to be able to follow movements more precisely, the pelvic plate had to guarantee a connection with a coupling that was as rigid as possible. Since the compliant behavior is realized through the pelvic module, the mechanical connection to the human user should be as rigid as possible [30]. For this reason, as a first precaution, it is necessary to think of a mechanical design capable of creating connection support between the plate and the user so that the pelvic plate can perfectly accommodate and follow his movements.
I moved on to the design phase trying to respect the following phases:

- evaluation and analysis of the problem by drawing up the prerequisites,
- actual design starting from sketches
- creation of a model in AutoCAD
- development of the model when it has satisfied all the requirements developed during the study phase
- testing and verification.

4.1.1 Preliminary Design Considerations

Whenever it is necessary to deal with a design process it is necessary to keep in mind certain phases. First, we ask ourselves what the project is supposed to do, why it is needed, and whether it can be tested in some way.
The second step is the creative brainstorming phase in which different solutions are hypothesized.
We then proceed by researching and analyzing the materials that will be used for the design task and then the first sketches are created.
Finally, it is necessary to proceed with the evaluation tests to understand if the results obtained satisfy the requirements or if improvements are necessary.

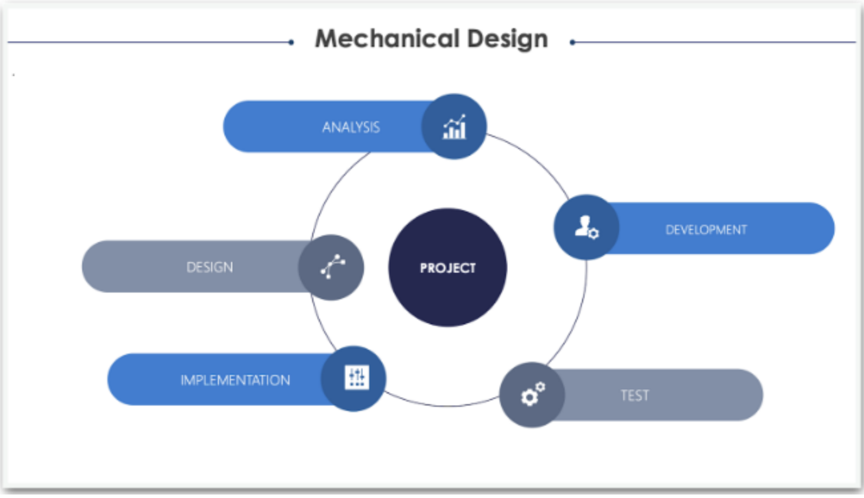


Figure 12: Mechanical design process

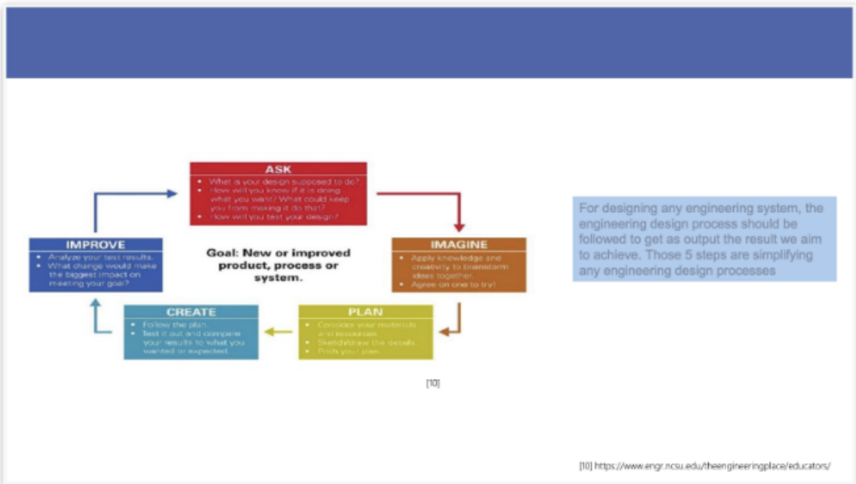


Figure 13: Phases of a mechanical design[42]

Following these preliminary considerations, I arrived at the definition of the requirements that the project needed:

4.1.2 Definition of Requirements

In defining the requirements to keep in mind when creating the connection plate project it must be:
-*Adaptable.* We have to guarantee that the support is between the 5th and 95th percentile to make it adaptable to the majority of the population.

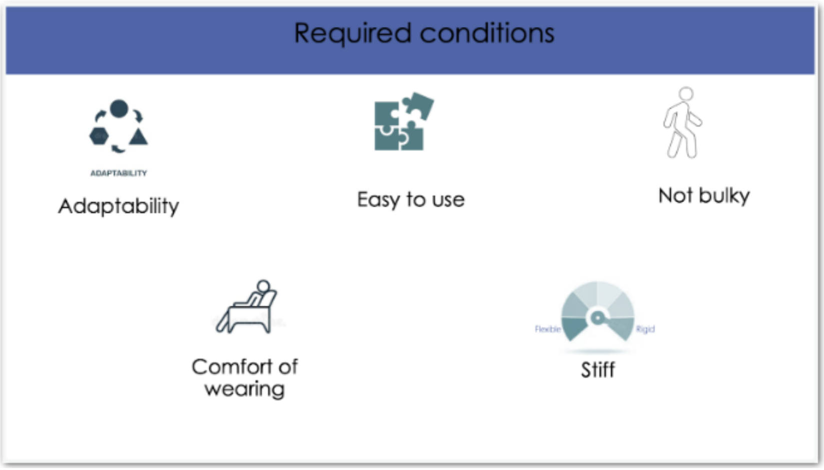


Figure 14: Required condition

-*Easy to use.* Dressing times are already very long and require a great commitment from physiotherapists.
It took too long time to adapt the robot to the user. For this reason, having to add another component, we cannot slow down this necessary time even further. For exoskeleton robots, long doffing/donning times are caused by the need to precisely align the axes of the robot's joints with human joints to prevent damage and awkward human-machine interactions [39]. *The goal is to make donning quick.*

-*Not bulky.* It is necessary to ensure that the patient and robot move in symbiosis without limitations in movement. For rehabilitation purposes, the patient must be supported without limits, even what could be, for example, the normal movement of the arms.

-*Comfortable.* Ergonomics is important, we need to study which points to associate the cushions with so that the structure does not rub against parts of the body also think about breathable materials that increase comfort.

-*Rigid.* Since compliant behavior is achieved through the pelvic module, the mechanical connection to the human user should be as rigid as possible.

4.1.3 Choice of Materials

The choice of materials is also crucial for the design of the exoskeleton connections. They must have good mechanical properties, and be robust enough to withstand the applied bending forces, but also lightweight to avoid excessive loading for the user and consequent discomfort.

4.1.4 Model Development

To meet all these needs I started by considering what types of movements I wanted the Lokomat to be able to follow. Trying to simulate the movement of walking and the passage of body weight from one leg to the other, I noticed that the pelvic plate was unable to follow the lateral movements, there was too much delay in the execution of these movements.

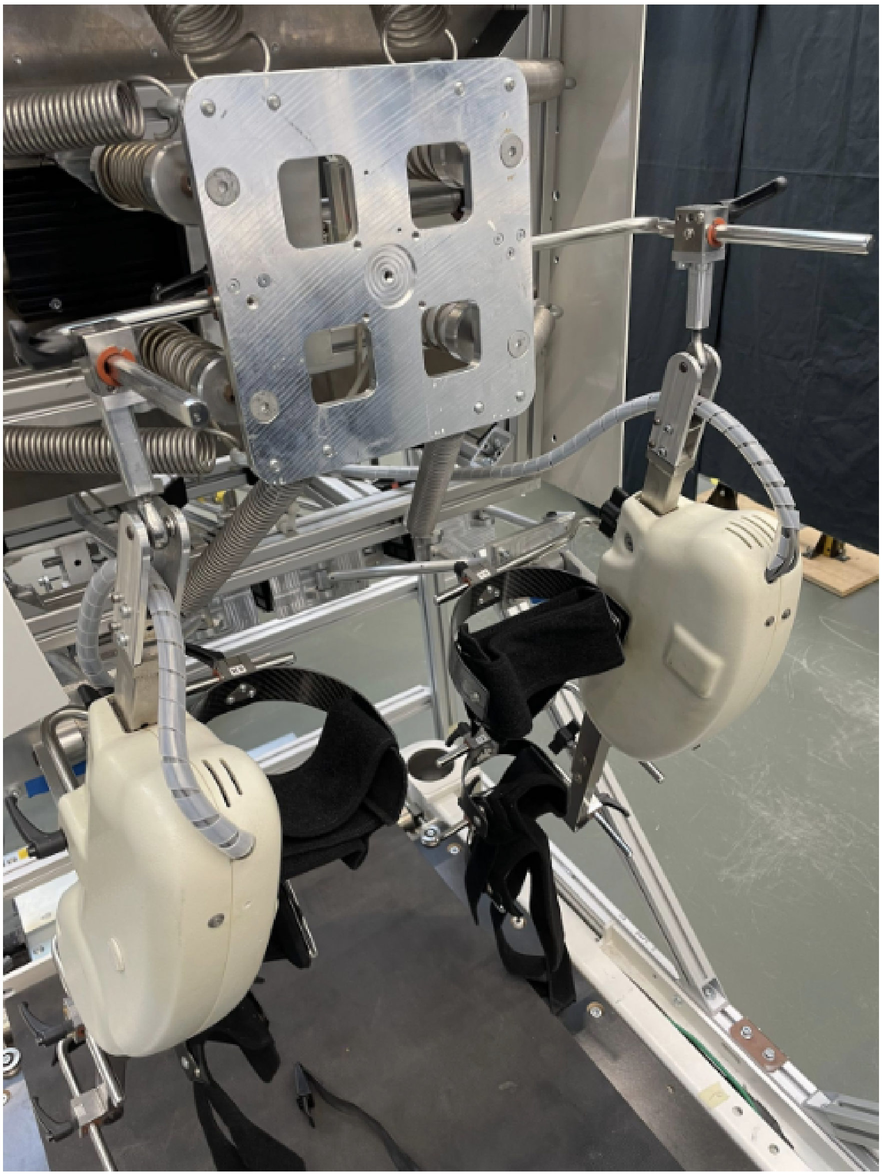


Figure 15: Lokomat Hocoma

In fact, as can be seen from Figure (15) there is no mechanism that can couple the robot with the user so every time the user tries to move the pelvis plate it will follow him with delays.
After several attempts it was useless to think about adding an additional harness to the one already in use, the solution didn't make much sense as well as being uncomfortable.

Figure 16: Lokomat and harness

So I came to the conclusion that it was necessary to use the already existing harness in some way to connect the plate to the patient.
The initial idea was to use a band and very simply create a hole behind the plate and create a connection using a carabiner.

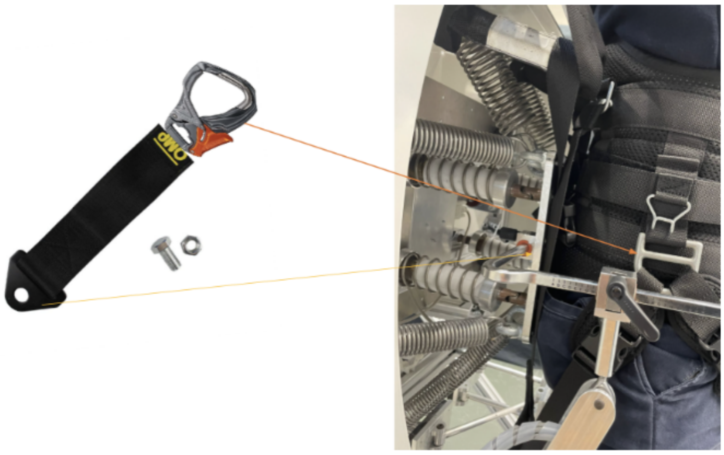


Figure 17: Connection to the plate

In this way, however, the plate followed the movements on the sagittal plane, therefore forwards and backward, but not in the lateral movements. However, the lateral movement accompaniment option is available in the Lokomat Pro so we tried to replicate this solution.

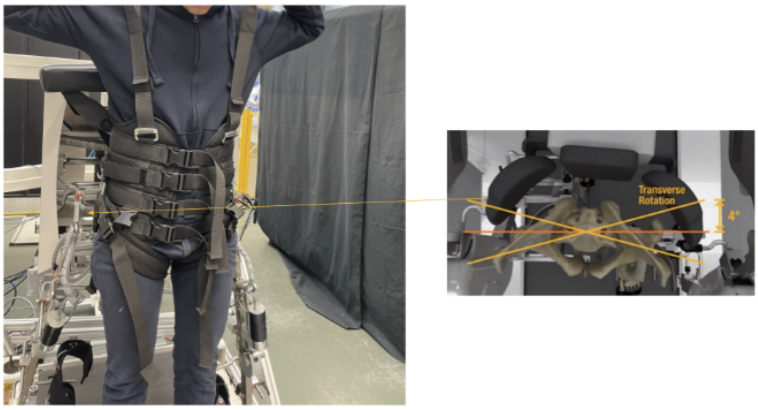


Figure 18: Initial idea (on the left Lokomat Pro[43])

The connecting element, however, had to respond to the need to modify its dimensions in so that it was adaptable to the different physical conformations of the users. In fact, a rapid adaptation method is necessary since the same must be used by multiple users shaped differently from each other and therefore avoid excessive times for restoring the functionality from the passage of the use from one patient to another.

Below I show the model that could potentially respond to these needs.

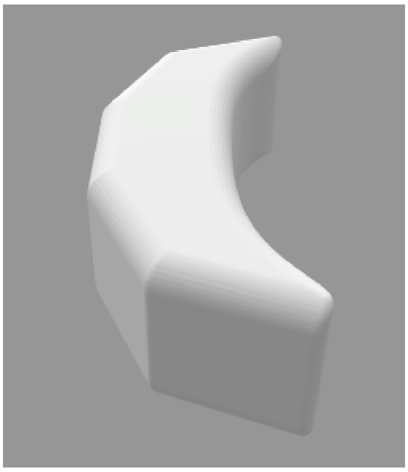


Figure 19: C-Shape

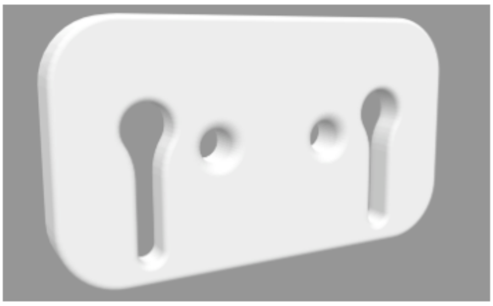


Figure 20: Plate for C-Shape

In the holes of the element shown in the Figure(20), the screws will be inserted and thanks to the grooves on the plate it will be easy to adapt the parts to the different dimensions.
A layer of hypoallergenic material will be applied to these supports.

4.1.5 Satisfaction of Requirements

The next step was to verify that the careful design met all the requirements. The checks demonstrated that the design adopted was able to satisfy the requirements because:

1. It is easy to use and has been adapted to what is already available on the Lokomat, the addition of this plate with grooves allows you to insert and remove this sort of "C" simply using a few screws.

2. The design is adaptable as it is possible to create different sizes of the prototype capable of adapting to the different conformations of the human body.
3. It does not interfere with the transparency of the entire system as it does not have a too bulky design. Consider that the patient will also have to wear a harness during rehabilitation which in no way should hinder normal walking.
4. The design is comfortable thanks to the addition of hypoallergenic padding that comes into contact with the human body, it has been fixed with the use of a tape.
5. The connection created by being rigid allows the pelvic plate to follow the patient's movements.

Below is the image of the final result of the model mounted on the Lokomat:

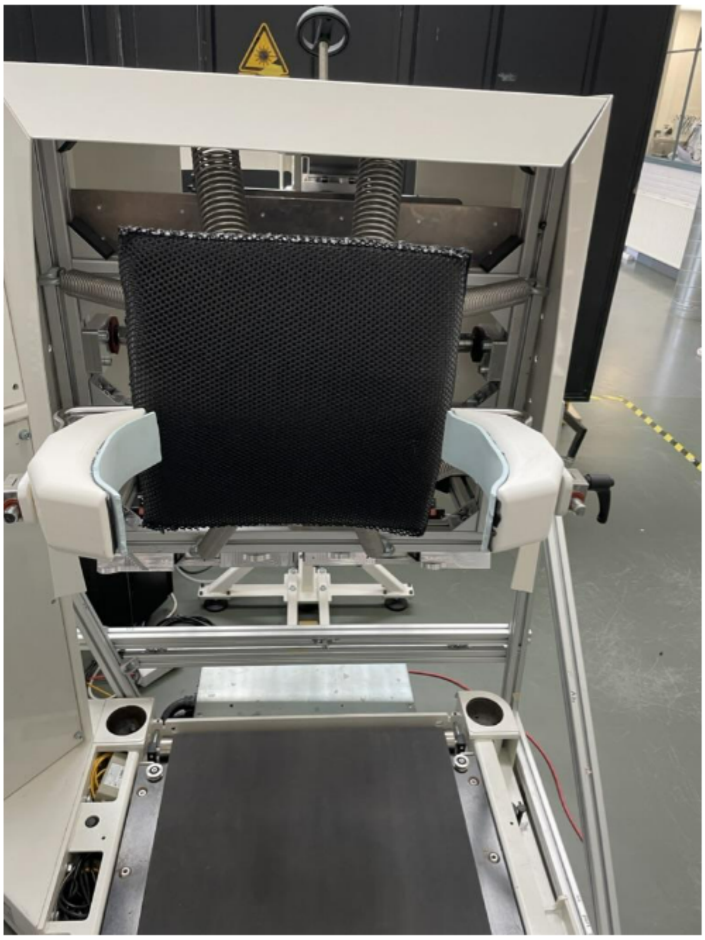


Figure 21: Final result

4.2 Sensors

To verify the project it was necessary to mount these C-shaped plates and carry out an experiment in which to compare the data obtained with and without support. Obviously, before moving on to this phase it was necessary to validate the functioning of the available sensors whether they were able to follow the trajectories, and whether it was not necessary to make changes before activation.

4.2.1 Inertial motion measurement systems

The sensor system used is composed of accelerometers and gyroscopes: inertial sensors. Their operation is based on the laws of dynamics or Newton, according to which bodies have the property of maintaining their linear and angular velocity constant as long as a force or a couple acts on them.
In addition to the inertial sensors, also called IMU (Inertial Measurement Unit), a camera was used. The data output from the sensors is nothing more than the orientations of the segments to which they are fixed concerning a global reference system of all the sensors.[30]
Although optical acquisition systems are the most accurate and precise, inertial units have numerous characteristics that make them valid for certain applications because they compensate for the limitations of optical instruments. For example, inertial sensors are much cheaper than cameras, have no limits in the measurement range, and, above all, they can be used in any environment, unlike stereophotogrammetric systems which can only be used in laboratories with fixed equipment.

The possibility of using them in any environment other than a specific laboratory, together with the possibility of producing accelerometers and gyroscopes in the micron range, has allowed IMUs to be increasingly used and to become one of the most valid systems in motion tracking.
The accelerometer, originally designed for use in aerospace applications, accelerometers are now used in many civil fields, such as car races, cellphones, testing, sports equipment safety, games, and so on. They are measurement tools that can detect an object's acceleration and calculate the force applied to its mass. A mass supported on an elastic component, a spring, is its basic working principle [33](Figure(22)). When a force acts on

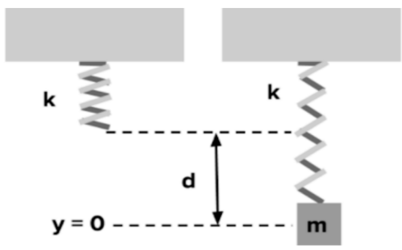


Figure 22: Mass-spring system underlying the operating principle of the accelerometer. [33]

an object, causing it to accelerate, the object undergoes a change in its state of motion and its modulus will be:

$$F = ma \tag{1}$$

Where m is the mass involved, a is the mass's acceleration, and F is the applied force. Hooke's law governs the spring's contraction or expansion in the region of linear operation, which is caused by the movement of the mass:

$$F = kx \tag{2}$$

Where F represents the generated spring force, k is the spring constant, and x is the displacement of the object. The equilibrium between these two forces results in a displacement x that is equivalent to the product of mass, acceleration, and the reciprocal of the spring constant, given by the formula $x = \frac{ma}{k}$. Therefore, by measuring this displacement, one can determine the acceleration according to the equation $a = \frac{kx}{m}$. By observing the motion of the mass in a specific direction, the system determines the acceleration along that particular direction. Specifically, a uniaxial accelerometer gauges acceleration exclusively along an axis corresponding to a specific orientation of the sensor. In contrast, a triaxial accelerometer captures three accelerations, each aligned with one of the three mutually perpendicular axes of the inertial unit. The orientation of the accelerometer dictates the direction of the recorded accelerations. When positioned on a segment and the segment undergoes a change in orientation, the direction of the measured accelerations also varies over time. (Peter M McGinnis, 2013).

The gyroscope is a rotating apparatus that, in adherence to the law of conservation of angular momentum, strives to maintain its axis of rotation consistently oriented. Through the detection of alterations in the direction of angular momentum, the gyroscope is capable of gauging angular velocity.[33]

It primarily comprises a torus-shaped rotor rotating around its own axis. When the

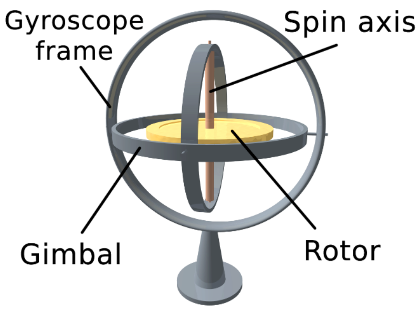


Figure 23: Components of a gyroscope.[33]

rotor is in motion, its axis demonstrates a tendency to stay parallel to itself, resisting any attempts to alter its orientation. If a gyroscope is affixed to a gimbal support allowing the wheel to freely orient itself in three spatial directions, the axis remains aligned even as the support changes orientation (Figure 23). Consequently, the rotor possesses three degrees of freedom, whereas the gimbal support has only two. According to Newton's second law, a body maintains constant angular momentum until subjected to a torque. The equation representing this principle is as follows:

$$\tau = \frac{dL}{dt} = \frac{d(I\omega)}{dt} = I\alpha \tag{3}$$

Here, τ denotes the applied torque, L is the angular momentum of the gyroscope, I is its moment of inertia, ω is its angular velocity, and α is its angular acceleration.

By analyzing the torque applied to the gyroscope, the device can measure variations in angular momentum and consequently in its instantaneous angular velocity. The gyroscope is adept at measuring angular velocity around a single rotation axis. Inertial sensors comprise triaxial accelerometers, measuring linear accelerations along three orthogonal directions over time, and triaxial gyroscopes, measuring angular velocities around the same three orthogonal axes over time. This combination provides information about the six degrees of freedom inherent in a body's motion.[33]

The IMU (MPU9250, Invensense, San Jose, USA) uses a three-axis accelerometer and a three-axis gyroscope and is sampled at a frequency of 1kHz.
The absolute position and orientation of the MUCDA end effector is determined via a miniature camera module and a 6 DoF inertial measurement unit (IMU).[30]
The camera is equipped with a filter permeable only to infrared light and tracks four

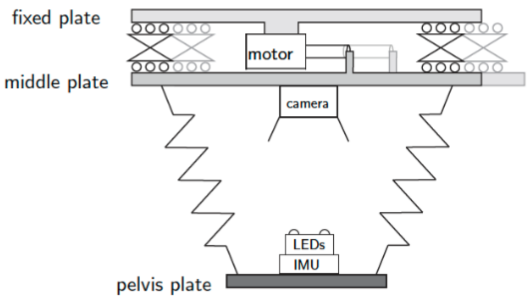


Figure 24: Sensing system with IMU, infrared camera and infrared LED-array [30]

active infrared markers (LEDs) mounted on the pelvic plate. The maximum spatial and temporal resolutions are 100 Hz and 0.14 mm, respectively.

A quaternion multiplicative extended Kalman filter, which provides detection of the position and orientation of the end effector, is used to combine IMU and camera data to estimate the position and orientation of the pelvic plate.[30]

4.3 4.2.2 Motion Capture Optitrack

The process of motion capture involves tracking the movements of the human body, and more, with a high level of precision in reproducing these movements [19] [21]. This system utilizes an array of cameras to record the motion of a subject adorned with markers. The acquired data is subsequently processed to generate a 3D representation of the subject's movements.

Motion capture systems are categorized based on the underlying hardware technology, and in this context, optical motion capture is employed, utilizing a sensor system integral to the research. The position of objects is determined by triangulating the light rays that interact within the space, rendering this category with the lowest latency.[33]

Marker-based systems leverage both active and/or passive markers [21]. Passive markers, covered in a reflective layer, are typically plastic hemispheres or spheres, which become highlighted when exposed to infrared light. On the other hand, active markers are commonly light-emitting diodes (LEDs) that illuminate in a specific sequence and frequency. Specialized cameras detect the presence of these markers, and computer software calculates their coordinates.

In the specific context of my research, passive markers were employed.[33]
A classic motion analysis system includes:

- Digital video camera
- A series of markers to place on the subject
- Specific software for the digital representation of movement[33]

First I had to calibrate the Optitrack system. This is essential for high-quality optical motion capture systems. During calibration, the system calculates the position and orientation of each camera and the amount of distortion in the captured image, which is used to create a 3D capture volume on the subject. It is done by observing 2D images from multiple synchronized cameras and matching the known locations of each camera's calibration marks through triangulation.
After positioning the markers and carrying out the calibration, it was possible to proceed with the experiment which involved the simultaneous recording of movements with the Lokomat sensor system with Simulink Realtime and the optitrack system.

4.2.3 Sensor validation

For this process the first thing to do is to synchronize the data from the IMU+camera system with the data collected by the optitrack to ensure that the sensor system is as precise as the optitracks, then it is necessary to check the relative positions of the plate, see if they are comparable and possibly find the error between the two measurements. This phase therefore concerned the validation of the sensors and to do this I performed a first experiment in which interaction with an internal user was not necessary; in fact it was sufficient to record the movements by moving the pelvic plate simply by applying forces in the three directions (x,y,z) with manual rotations, blocking the central plate, since the only data that were of interest were those obtained from the work of the pelvic plate, without taking into account of the movements between the two plates. The experiment was performed by simultaneously recording both data via optitrack and that of the

Lokomat sensor system.
The optitracks are the most accurate signal you can get and I wanted to compare whether the infrared camera data possibly combined with the Kalman filter could be used as an estimate.
Come pevaluation protocol to validate the sensing concept and evaluate the performance of the system, an additional external sensor system, the optitrack, was used.
To investigate the accuracy of the camera compared to optitracks, the tests were conducted using an evaluation device consisting of a pelvis support system and an optical tracking system. The calculated stiffness matrix was validated by blocking the lateral DoF of the pelvic module (so that the springs would flex to allow the pelvic plate to move and orient in 3D space.
The experiment was performed, for simplicity, at a sampling rate of 100Hz. The visible movements made at the beginning were performed to also calibrate the optitrack.
For translation, initially lateral movements, downward movements and finally compression-traction were performed. While the rotations were carried out first on the transverse plane and then on the sagittal and longitudinal plane. Regarding importing camera+IMU system data from simulink. The acquired data were saved in a MATLAB .mat file and used as input for the simulink that was available, what I did by modifying the simulink was to eliminate everything relating to the part relating to the use of the sensors in order to use the system offline and provide the data collected during the experiment as input.

```
% MATLAB
% Simulink data:
% Simulink translations, from the camera:
trans_data_cam = trans_camera.data;
translation_data = trans_data_cam(3:length(trans_data_cam), 1:3);

% Simulink rotations, from camera:
rot_data_cam = rot_camera.data;
rotation_data = rot_data_cam(3:length(rot_data_cam), 1:3);

xrot = x2.data(3:length(x2.data));  % This is the roll angle
yrot = y2.data(3:length(y2.data));  % Tilt angle
zrot = z2.data(3:length(z2.data));  % Yaw angle

% Filtered translations Kalman:
pos_Kalman_data = pos_Kalman.data;
position_data = pos_data_Kalman(3:end, 1:3);

pos_Kalman_x = pos_Kalman_data(3:fine, 1);
pos_Kalman_y = pos_Kalman_data(3:fine, 2);
pos_Kalman_z = pos_Kalman_data(3:fine, 3);

% Kalman filtered rotations:
roll_Kalman = yawpitchroll_Kalman.roll_phi.Data(3: fine);
pitch_Kalman = yawpitchroll_Kalman.pitch_theta.Data(3: fine);
```

```
yaw_Kalman = yawpitchroll_Kalman.yaw_psi.Data(3: fine);
```

Two data sets were recorded, one contained translations while the other contained rotations.
Once the movements were captured, the signals coming from the inertial units and the coordinates of the markers recorded by the camera were imported into the MATLAB work environment where the processing took place. I dealt with the manipulation of the data obtained via optitrack.

Once all the markers had been assigned to their label frame by frame, the spatial coordinates of the points of interest were made available, compatible with Excel, so it was possible to import the x, y, z coordinates of the various markers into MATLAB.
Both the inertial sensors and the camera, which recorded signals regarding the same gestures made by the subject, referred them to two different reference systems. In fact, as mentioned previously, the coordinates of the markers collected frame by frame by the Optitrack bar refer to the camera's own reference system. The data acquired by the inertial sensors are instead referred to a global reference system. As a result, the information collected by the two systems is not consistent with each other. To solve this problem, a common reference system was hypothesized, such that all data can be referred to.

Below is the code used to import optitrack data into MATLAB. Where the different indices used are the corresponding columns in Excel where to find the optitrack data of the basin and the x y and z frame.

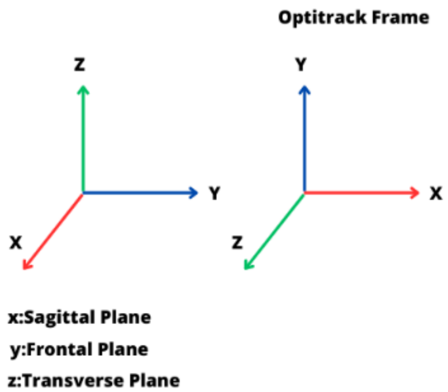


Figure 25: Optitrack frame

4.2.4 optitrack data conversion operations in matlab

Using data from a motion tracking system like OptiTrack in MATLAB involves some fundamental mathematical operations to convert and manipulate this data.

The main mathematical operations involved include:
-*Conversion from Quaternions to Rotation Matrices* (From OptiTrack frame orientation to a rotation matrix):
OptiTrack data includes quaternions to represent orientation. The conversion from quaternions to a rotation matrix.

-*Conversion from Rotation Matrices to Euler Angles.*
Transformation and Manipulation Calculations:
To perform transformation and manipulation calculations, we use multiplication operations between rotation matrices or perform mathematical operations on position vectors.
Relative rotation between two rotation matrices:$R_rel = R1/R2$
Relative position between two pointsp1 It isp2: $relative\_position = p1 - p2$
This was what I did:

Definition of rotation matrices:

- *Rt* it is an identity type rotation matrix, to make the two different coordinate systems coherent. Align the orientation of the OptiTrack system with the Lokomat sensor system. Using an identity matrix*Rt*.

Converting from quaternions to rotation matrices:

- *frame* is a vector containing four values representing a quaternion.
- *R1* is the rotation matrix obtained from the quaternion conversionframe in a rotation matrix

Calculation of the rotation matrix *R2*:

- *qpelvis_w, qpelvis_x, qpelvis_y,* It is *qpelvis_z* represent a quaternion associated with the position of the pelvis or pelvis.
- *R3* is the rotation matrix obtained from the quaternion conversion *qpelvis.*
- *R2* it is the result of *R1* raised to power-*1* (i.e. the inverse of *R1*) multiplied by *R3.*

Calculation of Euler angles:

- *eul* is a vector containing the Euler angles obtained by rotation. These angles are calculated using the rotation matrix *Rt * R2 / Rt.*

Euler angles are expressed in 'XYZ' order.

Calcolation vector position *r*:

- *pelvx, pelvy, pelvz* represent the components of the position of the pelvis.
- *framex, framey, framez* represent the components of a reference position.
- *r* is a vector resulting from the subtraction of *(pelvx - framex)*, *(pelvy - framey)*, *(pelvz - framez)* transformed using the inverse of *R1*.

```
%% Operation for optitrack data
idx_time_opti=2;
time_opti = dataset_opti(:,idx_time_opti)+time_delay_opti;
numsamples_opti=dimension(dataset_opti,1);
rx=[];ry=[];rz=[];Rx=[];Ry=[];Rz=[];
peri_sample=1:numsamples_opti
idx_bacino_x=27;
idx_bacino_y=28;
idx_bacino_z=29;
idx_frame_x=51;
idx_frame_y=52;
idx_frame_z=53;
pelvx = dataset_opti(i_sample,idx_pelvis_x) ;
pelvis = dataset_opti(i_sample,idx_pelvis_y) ;
pelvz = dataset_opti(i_sample,idx_pelvis_z) ;
framex= dataset_opti(i_sample,idx_frame_x) ;
framey= dataset_opti(i_sample,idx_frame_y) ;
framez= dataset_opti(i_sample,idx_frame_z) ;
qframe_x= dataset_opti(i_sample,47);
qframe_y= dataset_opti(i_sample,48);
qframe_z= dataset_opti(i_sample,49);
qframe_w= dataset_opti(i_sample,50);
qpelvis_x=dataset_opti(i_sample,23);
qpelvis_y=dataset_opti(i_sample,24);
qpelvis_z=dataset_opti(i_sample,25);
qpelvis_w=dataset_opti(i_sample,26);
Rt=[0 0 1; 100; 0 1 0];
frame=[qframe_w qframe_x qframe_y qframe_z];
R1=quat2rotm(frame);
R3=quat2rotm([qpelvis_w,qpelvis_x,qpelvis_y,qpelvis_z]);
R2=R1\R3;
eul=rotm2eul(Rt*R2/Rt,"XYZ");
Rx(i_sample,1)=eul(1);
Ry(i_sample,1)=eul(2);
Rz(i_sample,1)=eul(3);
r=R1\[pelvx-framex;pelvy-framey;pelvz-framez];
ry(i_sample)=r(1);
rz(i_sample)=r(2);
rx(i_sample)=r(3);
```

At this point it was necessary to synchronize the data collected both with optitrack and with the inertial sensor system to be able to compare them. We also worked to understand whether it was necessary to use the Kalman filter to obtain precise measurements on the position and orientation of the pelvic plate or whether the use of the camera was sufficient.
I then modified the Simulink model used in real time to be able to use it offline, giving as input the data recorded during the experiment.
A Simulink model *"Lokomat_kalman_observer.slx"* simulates the Kalman filter with pre-recorded sensor data.
The Kalman filter is largely based on code provided by Harald Nokland, University of Trondheim, in 2011.

4.2.5 Data analysis

Data analysis was conducted on pre-recording data relating to position and orientation.
As output I got:
The movements for the translations were performed in a deliberately slow and repetitive way, covering the three spatial directions: x, y and z. The first image, identified as 'translations-optitrack', offers a graphical representation of the data collected through the Optitrack system over time. This data provides a detailed view of the system's behavior during movements in three spatial directions.

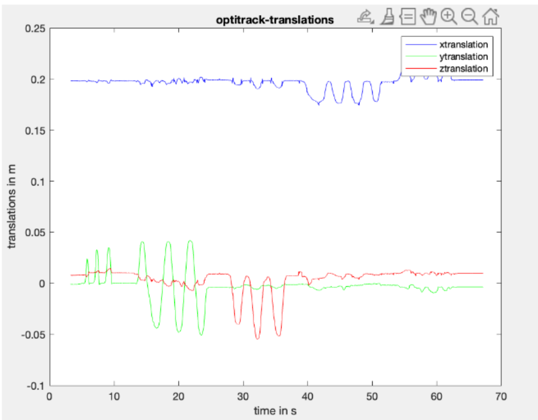


Figure 26: Optitrack-Translations

In the next figure, there is the graph of the translations along the x, y, and z axes, coming from the Simulink model used in the Lokomat with the appropriate modifications to allow offline use and obtained from the camera. From a visual comparison, it emerges that the data do not present significant differences. This suggests that the camera's performance may exceed initial expectations.

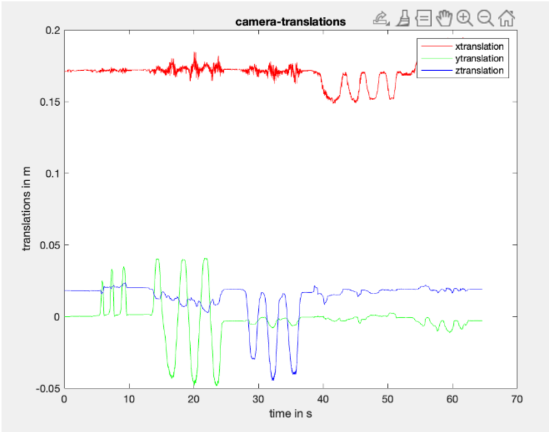


Figure 27: Camera-Translations

Secondly, we proceeded with a direct comparison between the data coming from Optitrack and that acquired via the camera. This analysis was conducted in order to evaluate any discrepancies and similarities between the two detection systems. As we can see visually, there are no significant differences.

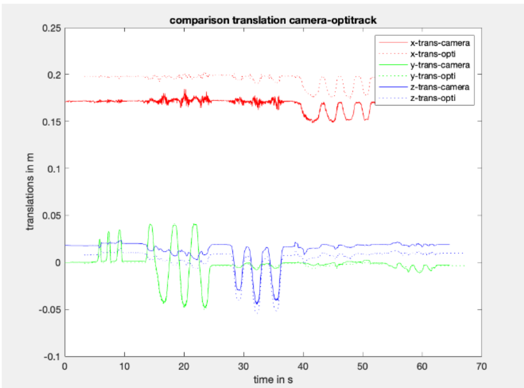


Figure 28: Comparison Camera-Optitrack Translations

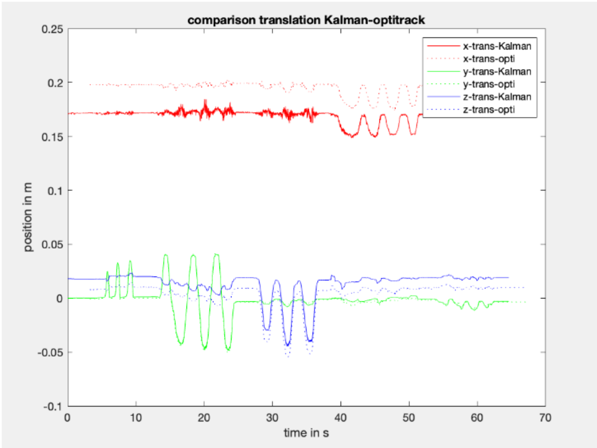


Figure 29: Comparison Optitrack-Kalman Translations

Finally, as already mentioned, in the above figure I have also compared the output data of Kalman with Camera and Optitrack, in the graph above we can see the comparison between Kalman and Optitrack which is the ground truth.

ROTATIONS

The same procedure was performed for rotations. The figure contains data regarding the rotations detected with the optitrack system as a function of time.

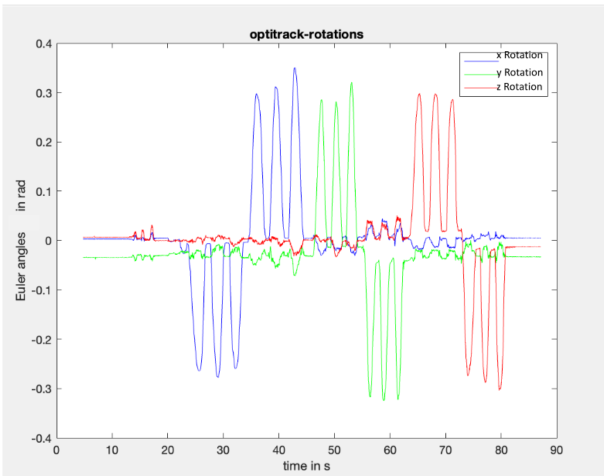


Figure 30: Optitrack-Rotations

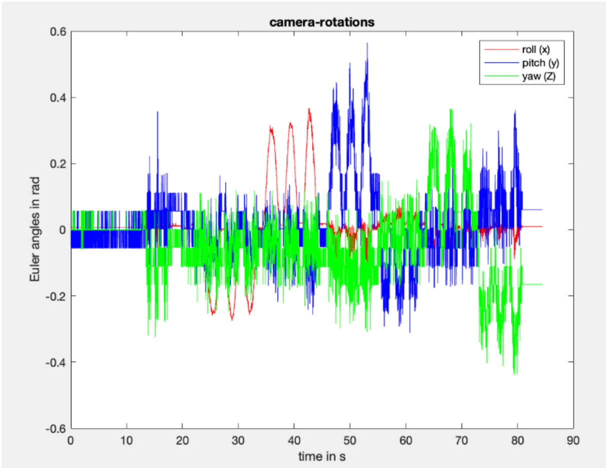


Figure 31: Camera Rotations

The second figure instead represents, as for translations, the rotations in x y z recorded with the camera, and in the third figure the comparison between the camera and optitrack, and gyroscope.

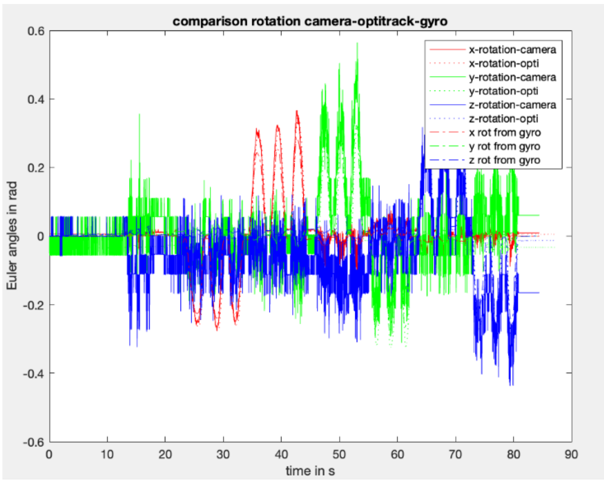


Figure 32: Camera-Optitrack-Gyroscope Rotations

In the figure below again a comparison between Kalman filter, optitrack, and camera.

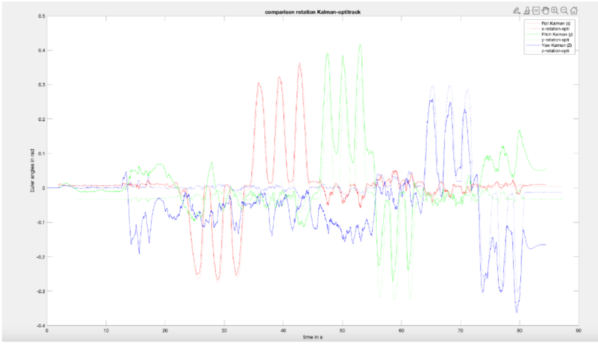


Figure 33: Camera-Optitrack-Kalman Rotations

As highlighted in the graphs, it appears that the use of the Kalman filter does not provide significant added value in terms of system accuracy. To further this evaluation, we compared the Root Mean Square Error (RMSE) values of position and rotation obtained from the Optitrack camera both with and without applying the Kalman filter. The following table presents the results of this comparison.

For position (translation), RMSE values in the x, y, and z directions were recorded for both conditions (with and without Kalman filter). The results indicate little difference in the overall RMSE values, suggesting that the Kalman filter may not make a significant improvement in the accuracy of the position measurement.

Regarding rotation, the RMSE values in the x, y and z directions show a similar trend. Despite some slight variations, the overall RMSE for rotation does not appear to be significantly affected by the application of the Kalman filter.

In conclusion, the data suggests that, at least in the specific contexts of this analysis, the use of the Kalman filter may not be essential to improve the accuracy of the position and rotation measurement provided by the camera.

Traslation

Table 5: RMSE Traslation table

	camera optitrack	kalman-optitrack
RMSEx	3.3011×10^{-4}	0,0264
RMSEy	9.6802×10^{-5}	8.8543×10^{-4}
RMSEz	1.3903×10^{-4}	0,0092
Overall RMSE	0,0308	0,0308

Rotation

Table 6: RMSE Rotation table

	camera optitrack	kalman-optitrack
RMSEx	0,0044	0,0042
RMSEy	0,0388	0,0398
RMSEz	0,0561	0,0560
Overall RMSE	0,2318	0,2236

4.4 Controller

First, to quantify the transparency of the module in the Y (lateral) direction, the pelvic module was unlocked and the control system was activated in zero-impedance mode. The handle was then manually moved periodically from left to right at different speeds, and lateral force (Y direction) and position data were recorded. It was also necessary to analyze and evaluate whether it was necessary to modify the controller that regulated the movement of the pelvic plate in relation to the midplate.
The present controller was a zero force controller and I took care of modifying it according to my needs.

4.3.1 Structure of the Controller Model

The model presents two distinct blocks, one for body weight support and one for the MUCDA, with a virtual wall that delimits the barriers within which movements are allowed. It was interesting for me to take care of the control part for MUCDA. A zero force controller must attempt to cancel out the resultant force, the system must exert a force equal and opposite to the applied external force.

I developed a list of possible points that need to be met and tried to provide solutions to these questions at the time of implementation.
The primary objective was to adjust the position so that the pelvic module followed the human's movements in a fluid and precise manner, so if a movement was applied between the frontal plate and the intermediate plate it was necessary to apply a force to make so that the central plate follows the front.

4.3.2 Requirements

1. -*Tracking*: Allows the pelvis module to track the movement of the pelvis plate. The center plate should follow the movement of the plate without significant delays or tracking errors.

2. -*Stability*: the pelvis and central plate must maintain a stable position and balance during the movement without oscillations or instability, it is for this reason that my choice fell on the implementation of a PD controller.

3. -*Reactivity:* should respond quickly to changes in pelvic plate movement. This means that we should minimize friction which improves the responsiveness of the system with smoother and more precise movements.

4. -*Limitation of lateral movement:* Limit lateral movement of the pelvic plate to maintain stability or prevent lateral displacement.

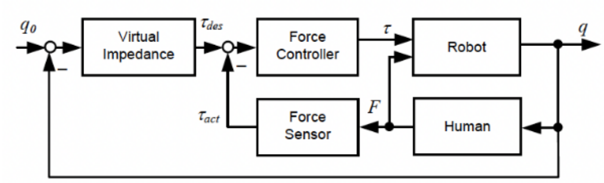


Figure 34: Example for an independence control architecture used to make the rehabilitation root behave compilant.[35]

This is an example of an impedance controller on which is based the controller I later developed .

- *q0* represents the desired position so it is the value of the position that the controller tries to chase
- Virtual Impedance simulates the elastic behavior, which will be given by the desired displacement multiplied by the virtual force
- Tdes is the desired virtual force
- The force controller converts the desired virtual force, and generates adequate reaction force for the system to realize the desired motion-tracking

4.3.3 Friction compensation

Friction was also taken into account in the implementation of the controller, correcting it with a friction compensation term according to the formula:

$$Fa = Fcoul + Fvisc \tag{4}$$

$Fa = bdx' + bssng(x)$ this is the term that describes the friction force, where the first term is the dynamic friction force and the second is the static friction.[34]

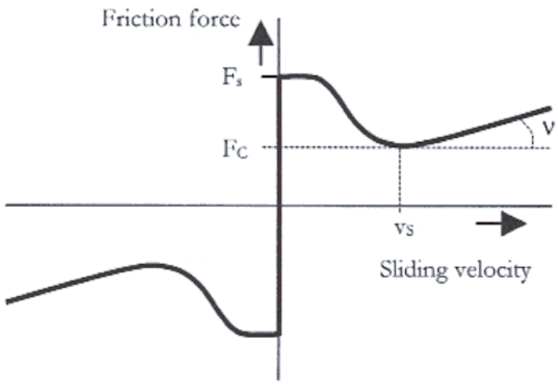


Figure 35: Friction force [34]

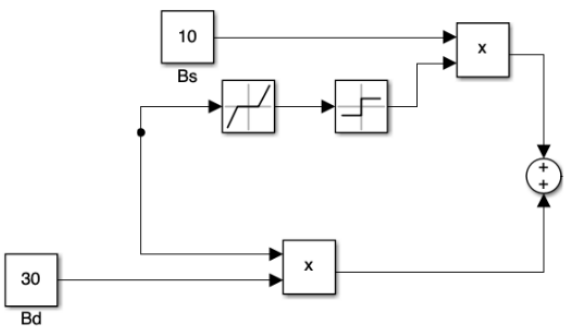


Figure 36: Friction compensation Simulink model

The bs and bd values were taken from the system identification carried out for another project also on the Lokomat.

The complete model is as follows:

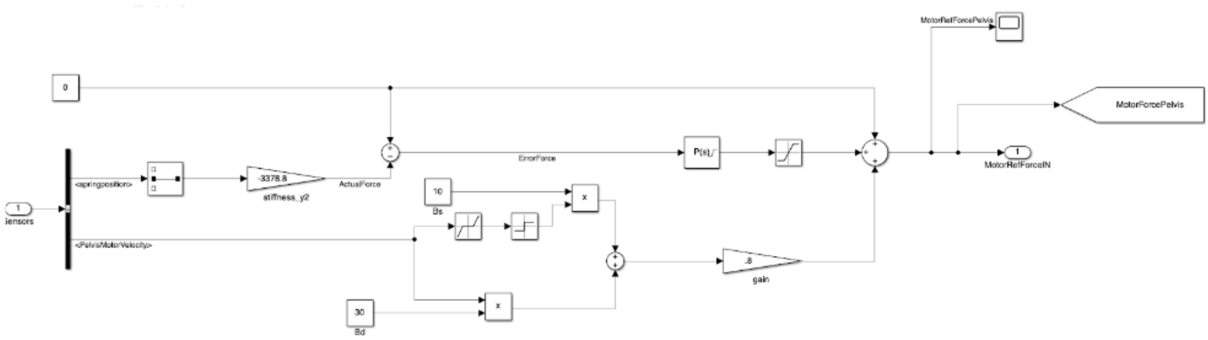


Figure 37: Complate simulink controller model

The equation that describes the model is:

$$F = k(desired\_position - real\_position) + Fa$$
$$F = k((SpringPosition + MotorPositionpelvis) - MotorPositionpelvis) + (Fcoul + Fvisc)$$

5 Results and discussion

5.1 Experimental protocol

Evaluation of the effect of inserting the pelvic design and controller on the Lokomat system.
Objective of the experiment: The objective of this experiment was to evaluate the effect of including the pelvic design and controller on the Lokomat system in terms of human motion tracking. *Hypothesis*: The hypothesis to be tested is given by the integration of the new design of the pelvic plate and the pelvic controller which will lead to improving the ability of the Lokomat system to track human movements. With better tracking of the pelvic module during walking I expect better coupling. The created shape will adapt to human hips and improve mechanical rigidity.

Materials and equipment:

- Complete Lokomat system (no legs attached to the human; legs will be removed from the Lokomat before conducting the trial)
- Treadmill
- Harness and BWS

- C-shaped pelvic attachment 

- Sensors (camera and IMU)

- Computer con software MATLAB Simulink

Experimental procedure: The participant was required to walk inside the Lokomat during the experiment. Before starting the experiment, participants were asked to provide personal information regarding weight, height and age, and were asked to indicate their general preferred walking speed on the treadmill.
The walking speed is chosen in a range between 1 and 3 m/s, based on the participant's normal walking pace or preferences, to find the right compromise that makes the participant feel comfortable during the walk. The speed was set so that participants could perform the movement without risk or discomfort. Furthermore, the speed had to be consistent with the experimental conditions to avoid observed differences arising from speed variability.
Participants were asked to read and complete the informed consent form and to answer any questions or concerns related to the experiment.

Experimental setup: Position of the participant on the Lokomat platform.
To ensure safety and support, the participant will be asked to wear the harness, which will be connected to the body weight support system. Height adjustment of the Body Weight Support (BWS) and Lokomatche must be customized based on the participant's height.
Connection of sensors (camera and IMU). Configuring the Lokomat system and MATLAB Simulink software for acquiring and processing data from sensors.
Starting the treadmill to make the participant's walking.

Execution sequence: Performe the first execution of the experiment: Run with the C-shaped pelvic attachment and the pelvis controller on. Second running the experiment: Running without the C-shaped pelvic attachment and with the pelvis controller turned off.
Third execution of the experiment: Run without the pelvic C-attachment but with the pelvic controller on. Fourth execution of the experiment: Run without the C-shaped pelvic attachment and with the pelvis controller turned off.
The participant is required to walk for 5 minutes for each condition, for a total walking time of 20 minutes.
At the end of each run, the participant was given a rest period during which they were asked to complete a feedback questionnaire.
The experiment, including breaks and filling out the questionnaire, lasted a maximum of 1 hour in total. The study was conducted with at least 5 participants in order to obtain an average across multiple individuals.

5.2 Data analysis

During each run of the experiment, data from the sensors, including camera and IMU signals, were recorded and correct synchronization of the data during recording was ensured. Metrics of the results considered: *Lateral movement:* the sum of the displacements of the two plates, the pelvic plate and the central plate, was considered. This provided an overall measure of system response. Instead of considering the data obtained from the faceplate, I obtained information about the forces between the participant and the system. *User comfort:* the level of comfort and satisfaction reported by the user during interaction with the Lokomat system was evaluated. Questionnaires or rating scales were used to collect subjective feedback from the user. Quality of coupling: Evaluate whether the participant detects any resistance during walking.

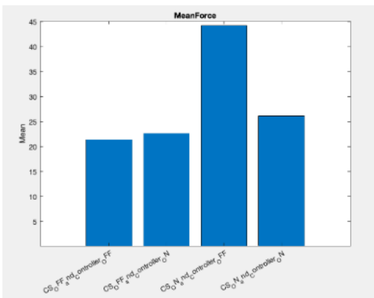
The valid movements to be investigated were lateral translations, forward/backward movements (sagittal plane), as well as lateral rotations. These movements represent a significant range of movements for the interaction between the Lokomat system and the user. Evaluating the effectiveness of the pelvic module design in allowing the robot to accurately track these movements without delays or deviations provided substantial evidence of the effectiveness of the research. Including these movements in the evaluation certainly improved the understanding of the interaction between the robot and the user during Lokomat-assisted walking.
Measuring and analyzing the displacement, the alignment between the robot and user movements, and the absence of delays in the system response served as relevant parameters to evaluate the effectiveness of the new pelvic module design.

5.3 Quantitative data analysis

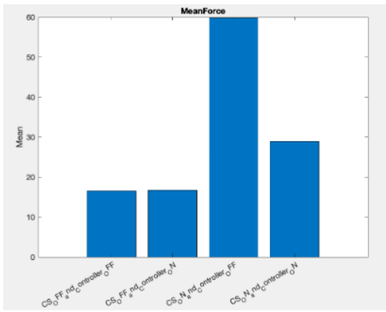
The experiment was conducted with 4 healthy participants, 3 of whom were male and 1 female. What we can notice from the analysis of the movement of the participants is that:

Mean Force:

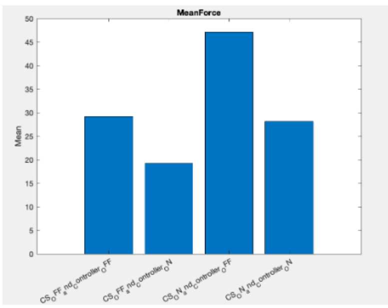
The average force is greater when the C-shaped pelvic is active and the pelvis controller is deactivated.
The average force is lower when both the C-shaped pelvic attachment and the pelvis controller are deactivated.
The other two conditions C-shaped pelvic attachment deactivated and pelvis controller active, C-shaped pelvic attachment active and pelvis controller active show intermediate values.



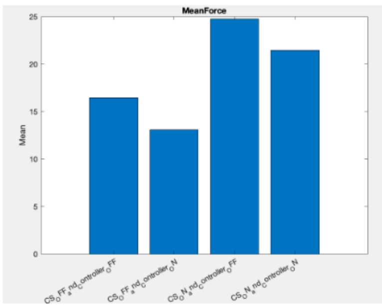
(a)



(b)



(c)

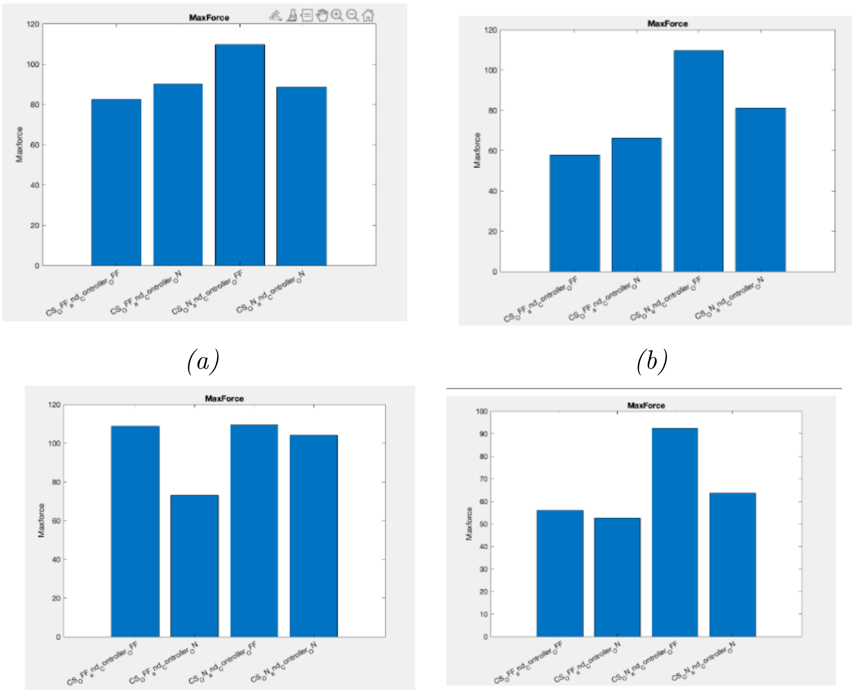


(d)

Figure 38: Medium Strength

Maximum Force:

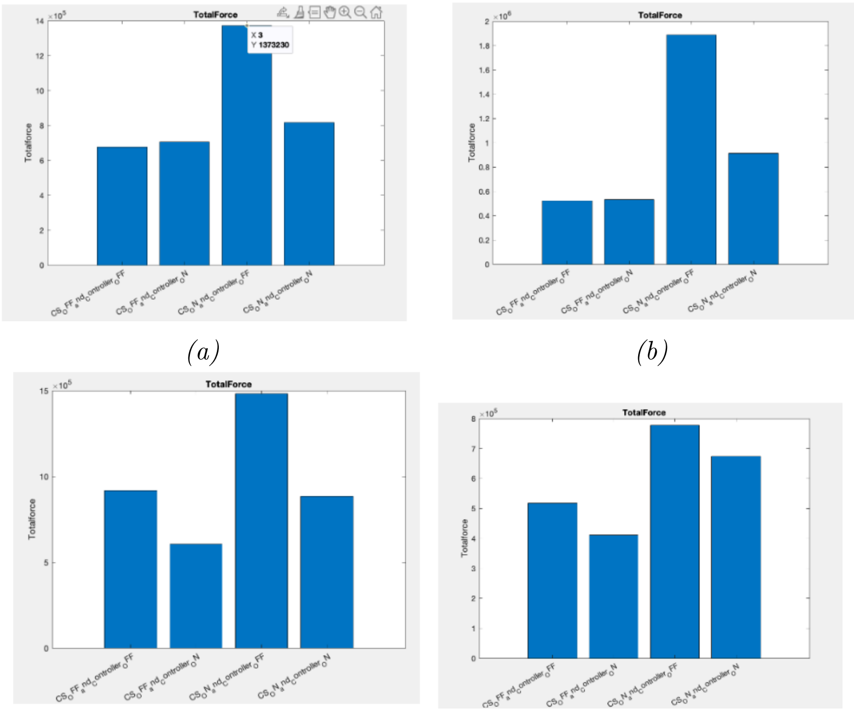
The same can be said for the maximum and also for the total force as shown in the graphs below:



(a) (b) (c) (d)

Figure 39: Maximum Strength

Total Force:



(a) *(b)* *(c)* *(d)*

Figure 40: Total force

In general, as seen, the force is greater when the controller is deactivated and when the C-shaped pelvic attachment is active, which could indicate a greater adherence of the device to the human body. This adherence could result in a better coupling between the Lokomat system and the user, allowing the plate to follow the user's movement more precisely.

However, this improved grip may require more force from the user to move. For example, if the device is "stiffer" when the C-shaped pelvic attachment is active, the user may have to apply more force to overcome the friction and move. Also, if the plate follows the movement more precisely, there may be more resistance from the system.

Displacement

As already noted, analyzing the acting forces, it seems that the activation of the C-shaped pelvic attachment and the pelvis controller also has a significant impact on the displacements in the various directions such as x, y and z. We can see how in the case of the movement on the x axis, except in the last case, it is significantly greater when the c-shaped and controller are active, while the movements are lower when the c-shaped is deactivated. On the y axis it is interesting to note how the movement is greater when the c-shaped is activated but the controller is deactivated. While as regards the z axis it is not possible to identify a specific pattern.

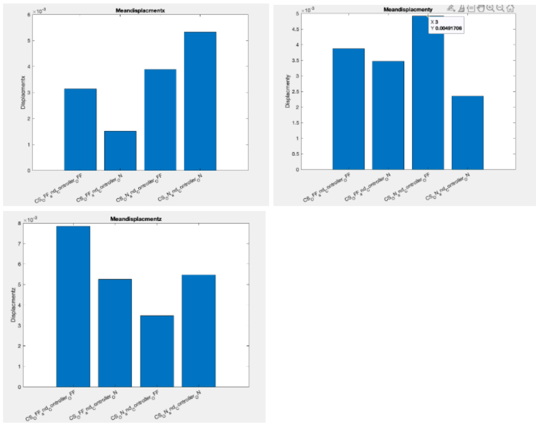


Figure 41: Displacment x,y,z, Partecipant 1

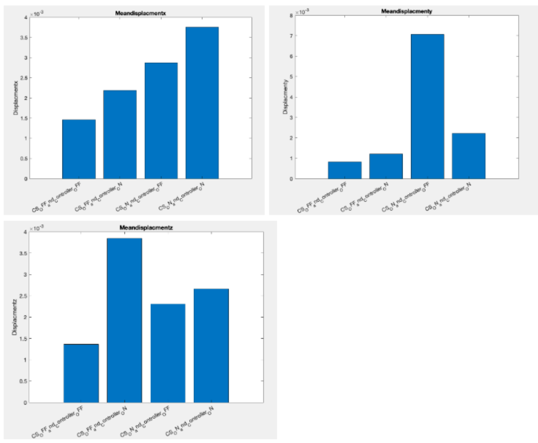


Figure 42: Displacment x,y,z, Partecipant 2

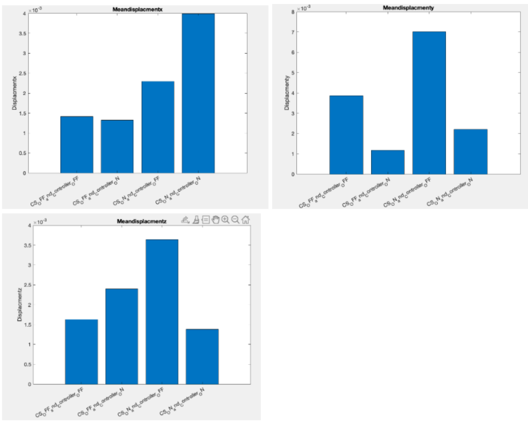


Figure 43: Displacment x,y,z, Partecipant 3

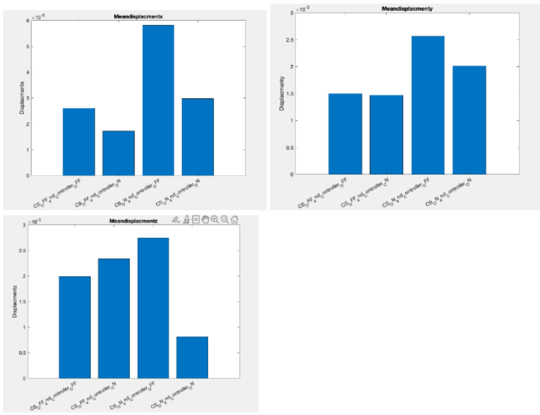


Figure 44: Displacment x,y,z, Partecipant 4

QUALITATIVE RESULTS

Here is a summary of the data that emerged from the participants' responses in the different experimental scenarios:

C-Shape On and Controller On:

- They found a responsive response to the commands given.
- They felt a rigid connection, but one that was able to follow their movements.
- No jerky movement or delays, with movement synchronized between the participant and the Lokomat.
- They find the connection quite comfortable, even if they feel some pressure on their hips.

- Overall, they rated the device as quite comfortable.

C-Shape On and Controller Off:

- Reactive response, but less than when the controller is active.
- Perception of medium rigidity with ability to follow movements.
- No jerky movement or delays, but the movement is less synchronized with the device.
- They feel more pressure on their hips, but still find the connection quite comfortable.
- Overall, they rated the device as quite comfortable.

C-Shape Off and Controller On:

- Quite responsive response, but less than when the controller is deactivated.
- Perception of medium rigidity with ability to follow movements.
- Smooth movement, but with delays between the participant and the Lokomat.
- The movement is poorly synchronized with the device and there is play between the body and the robot.
- No pressure felt, but they still find the connection quite comfortable.
- Overall, they rated the device as quite comfortable.

C-Shape Off and Controller Off:

- Less responsive response than other scenarios.
- Perception of a less rigid connection and average ability to follow movements.
- Smooth movement, but with significant delays between the participant and the Lokomat.
- The movement is poorly synchronized and there is play between the body and the robot.
- No pressure felt, but they still find the connection quite comfortable. Overall, they rated the device as quite comfortable.

General preference: All 4 participants expressed a preference for the condition in which both the controller and the C-Shape were active.

From the qualitative data and the preferences expressed by the participants when both the controller and the C-Shape are active, several advantages seem to emerge:

Reactive Response and Synchronization:
Participants noted a responsive response to commands, suggesting that the system responds effectively and promptly to desired movements.

Synchronized Movement:
The perception of a synchronized movement between the participants' body and the Lokomat suggests that the simultaneous activation of the controller and the C-Shape contributes to better coordination between the movements of the user and the device.
General Comfort:
Despite the observations of stiffness and pressure on the hips, participants overall rated the condition in which both the controller and C-Shape are active as quite comfortable.
Users Preference:
All four participants expressed a preference for the combination of controller and active C-Shape on, that offers a positive perception and a better user experience compared to the other conditions tested.
Better Mechanical Adaptation:
The system's ability to follow participants' movements, combined with a responsive response, indicates good mechanical adaptation. This can be crucial to ensuring an effective rehabilitation experience.
Possible Reduction of Delays and Jerky Movements:
The preference for this condition suggests that simultaneous activation of controller and C-Shape could help reduce delays and jerky movements found in other conditions.
Overall Mate Quality Improvement:
If participants perceive an improvement in the device's ability to follow their movements in a synchronized manner, this suggests an overall improvement in the quality of the coupling between the body and the Lokomat. Activating the controller and C-Shape at the same time appears to offer a combination of benefits, including improved responsiveness, synchronization, overall comfort, and mechanical adaptation, according to participants' perceptions and preferences. These benefits can be crucial for effective rehabilitation and improving the overall user experience with the Lokomat device.

5.4 Discussion of Results

The discussion of the results will focus on the analysis of the performance of the Lokomat system considering both the implementation of the new C-Shape device and the introduction of the pelvic controller. The results emerging from this study provide a complete overview of the effects of both elements on movement dynamics, applied forces and user perception during assisted walking. Some key considerations include:

1. **Responsiveness and Synchronization:**
   In cases where both the C-Shape and the controller are active, participants experienced a responsive response and synchronized movement with the Lokomat. This suggests that implementing both elements can improve the interaction experience.

Reactivity and synchronization are crucial aspects for effective assisted walking.

2. **Mechanical Adaptation and Movement Tracking:**
   The perception of a certain rigidity in all conditions, but also of the system's ability to follow the participant's movements, indicates good mechanical adaptation. This is crucial to ensure that the Lokomat can follow the patient's natural movement without unwanted deviations.

3. **Forces and Displacements:**
   Quantitative results show that the average force and maximum force are greater when the C-Shape is on and the controller is off. This may indicate that activating C-Shape contributes to a greater adherence of the device to the human body, but may require greater force from the user to move. Lateral displacements are significantly greater when both the C-Shape and the controller are active.

4. **User Comfort:**
   Overall user comfort ratings indicate that despite some observations of pressure on the hips, the system is overall considered quite comfortable. This suggests that, despite some differences in specific perceptions, the implementation of C-Shape and the controller is acceptable to users.

5. **Users Preference:**
   All participants expressed a clear preference for the condition in which both the C-Shape and the controller were active. This preference indicates that the combination of both elements offers a positive perception and a better user experience compared to the other conditions tested.

The joint introduction of the new C-Shape device and the pelvic controller in the Lokomat system influenced positively the movement dynamics and perception of users during assisted walking. The combination of both elements offers an integrated solution that, according to qualitative and quantitative data, can lead to better responsiveness, synchronization and overall comfort during rehabilitation therapy. These findings provide a solid foundation for further research and development in the field of rehabilitation robotics.

With activation of the C-shape and the controller the dynamics that can occur are:

Force: With better adaptation of the "C" shaped pelvic attachment and active control of the pelvis, fewer forces should be applied to maintain synchronization between the participant and the Lokomat.

Displacement: The goal of the Pelvic C-Shape and Pelvic Controller is to improve detection of pelvic motion (displacement), wesee increased displacement compared to other

conditions. In other words, the pelvis follow the participant's natural movement better, so more "shift" would be seen than in other conditions.
User convenience: It is the participants who report greater or lesser comfort during this condition, as the goal is to improve the walking experience.
Better coupling: The participants feel a greater correspondence between the natural movement of their body and the movement of the Lokomat and this should be reflected in the coupling quality data.

With the controller and the C-shaped pelvic attachment are both deactivated, it is possible to observe some specific dynamics:

Displacement: In this condition, the "shift" is likely to be less than in conditions where the controller and pelvic "C" attachment are active. Without the active control and support of the C-shaped structure, the participant's pelvis will have a greater range of motion, which may result in less displacement than the desired motion.

Force: Observe the need to apply more significant forces to maintain synchronization between the participant and the Lokomat system in the absence of an active controller and structural support. Forces can vary greatly during walking, as the system may have difficulty tracking the participant's movement without active control.

User convenience: User comfort decrease in this condition, as the participant feel less supported and more unstable while walking.

Better coupling: The quality of the coupling is compromised without the active controller and pelvic "C" mount support. The participants feel less fit between their movement and the movement of the Lokomat.

Overall, this condition with no active controllers and no structural support represent a situation where the Lokomat system has less influence on the participant's movement and the participant has more freedom of movement.

With intermediate conditions, i.e. one with the controller on and the pelvic C" attachment off and another with the controller off and the pelvic C" attachment on, we see an intermediate dynamic.

Controller active, Pelvic C-Shape deactivated:

Displacement: In this condition, a similar to the condition where both are turned off. The active controller can help maintain better alignment between the participant's movement and the Lokomat, even if the "C"-shaped pelvic attachment is not active.

Force: The forces is stable and slightly lower than in the condition where both are turned off.

User comfort: User comfort is better than when both are turned off, but still not be at its best in the absence of structural support.

Controller off, C-shaped pelvic attachment on:

Displacement: In this condition, a slightly better shift can be observed than in the condition where the controller is off and the "C" shaped pelvic mount is on. The “C” shaped pelvic attachment will help provide structural support.

Force: It is necessary to apply slightly higher forces than when the controller is active. However, structural support can help keep the movement more stable.

User comfort: User comfort may be better than when the controller is deactivated and the "C" shaped pelvic mount is active, but may still not be at its best without the active controller.

Future Works:

During the experiment, an important aspect emerged related to the users' perceptive experience when using the Lokomat system. Users reported that despite clear benefits in terms of structural support and synchronized movements, the overall sensation during assisted walking did not fully reflect the natural walking experience. In particular, it was noted that arm swing, an essential and spontaneous component in normal walking, was limited while using the Lokomat. This aspect underlines the importance of considering not only the biomechanical and functional aspects but also the perceptive and subjective ones in the implementation of rehabilitation systems. Future developments may explore ways to allow greater freedom of movement in the arms, thus contributing to greater user immersion during robot-assisted rehabilitation therapy.
Usability of the Material and Adaptability to Different Body Sizes: During the implementation of the C-Shape device, another critical aspect highlighted concerned the usability of the material used. The 3D printed component solved some challenges in terms of ease of insertion and removal, especially regarding the mating between the C-Shape and the plate. The adaptability of the device measurements could be a point of attention to focus on. Different body types may require custom sizing to ensure an optimal fit and positive user experience. Possible future developments could, therefore, explore the use of alternative materials with improved flexibility and adaptability properties, as well as the implementation of adjustable or customizable sizes to ensure greater versatility of the device with respect to various user morphologies.

Pelvic Controller Optimization:
The effectiveness of the pelvic controller in improving reactivity and synchronization during assisted walking represented the fulcrum of the study that led to the writing of this thesis which, however, left some questions still open. In fact, it is possible to explore further perspectives to optimize this component. A future area of development could involve the implementation of advanced control algorithms that dynamically adapt the system's response to changes in users' walking patterns. Introducing machine learning capability could allow the controller to adapt in real-time to the specific needs of each individual, further improving the personalization and effectiveness of rehabilitation therapy. Furthermore, exploring alternative control modalities, such as proportional-integrative-derivative (PID) control or neural network-based approaches, could offer new opportunities to refine control precision and dynamically adapt to various walking conditions.

6 Conclusion

This thesis work had as its objective the search for an innovative design followed by the design of a pelvic plate that would allow a correct interaction between the rehabilitation robot and the user. The activity was preceded by reading of the existing literature on the subject of rehabilitation exoskeletons in order to fully understand what the requirements were to be met for the solution of the problem presented to me. In light of the data analyzed, a series of results can now be proposed: An improvement in motion detection: We expect to see a substantial improvement in the Lokomat system's ability to accurately track participants' movements during walking, thanks to the implementation of the C-shaped design and pelvic control. It is expected that this improvement will result in better adherence of the system to the movements of the participants, contributing to greater precision in rehabilitation therapy.

A reduction in delays: Effective pelvic control is expected to lead to a significant reduction in lateral movement delays during control activation. We predict that this reduction in delays will be evidenced by differences in movement trajectories between conditions with and without pelvic control. Delay reduction is critical to providing a timely and synchronized response to participant actions.

Greater range of motion: The implementation of the C-shaped design is designed to improve the coupling between the Lokomat system and the participant, resulting in a greater range of lateral movement. This result is particularly relevant to ensure effective rehabilitation therapy and promote more natural movements during assisted walking.
The expectation is therefore that with the activation of both the C-Shape and the controller the displacements will be greater and the forces smaller, while when everything is deactivated there will be greater forces given by friction and smaller displacements.

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