State of the Art on Lower Limb Rehabilitation Robots

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Abstract: Due to the increasing number of people suffering from walking disorders, physiotherapy is becoming the process of treating this dysfunction and helping people to recover their natural motor ability as much as possible. Due to the lack of therapists, rehabilitation robots aim to reduce their tasks, help patients recover their natural walking ability as much as possible, and promote self-rehabilitation. The present work reviewed the state of the art of lower limb rehabilitation robots and introduced their features, including structure, drive mode, control and safety precautions. Then, we discussed the problem of developing the current rehabilitation robots and the orientation towards the future.

Keywords: rehabilitation robot, lower limb, safety precautions, range of motion.

1. INTRODUCTION

The lower limbs are among the major organs for human mobility and autonomy. They are involved in locomotion and thus enable walking, running, jumping, etc. Their structure also makes it possible for humans to maintain a stable position. A lower limb injury or injury leads to walking problems or a noticeable disability. When an impairment occurs, recovery of motor function can take a great deal of therapist time and effort depending on the state of injury and treatment method. An adapted rehabilitation allows the rapid recovery of the autonomy of the motor functions of the affected subject and maintains the body in balance during the movement. In the traditional rehabilitation method, patients depend on physiotherapists to carry out their treatment. With the shortage of therapists and the sharp increase in people with lower limb disorders, it has become necessary to follow new rehabilitation methods. Therefore, rehabilitation technology through the application of robotics is a promising solution. Rehabilitation robots allow patients to train independently with less supervision from a therapist, provide precise and even training, help them restore their motor functions and recover or compensate for lost movement and give them the ability to complete the most basic life. In this work, we presented the joint physiology of the lower limbs and their injuries. Then we began the state of the art related to lower limb rehabilitation robots, the detailsconcerning the design of the robot, its hardware control system and safety precautions. Then, we carried out a study of the problem of rehabilitation robots with the proposal of some solutions. Finally, to conclude our work, a conclusion was presented with an orientation on future research on our research topic.

2. JOINT PHYSIOLOGY OF THE LOWER LIMBS

The lower limb has three joints, the hip is the fundamental joint of walking, connects the femoral head with the articular cavity of the pelvis. It is driven by the most powerful muscles in the body, especially the gluteal muscles. The hip joint is mobile in all planes, back and forth (flexion/extension); laterally (adduction/abduction); and rotation (internal/external).The knee, which provides stability to the lower limb, is a vulnerable joint that experiences high stresses from daily activities, such as lifting loads and kneeling, and activities at high impact, such as jogging and fitness. It is very stressed when walking or running[1]. The movements of the knee can take place in the sagittal plane, the movements of flexion/extension along the transverse axis and the movements of rotation around the longitudinal axis. When flexing, there is automatic internal rotation; when extending, there is automatic external rotation. The ankle is the joint that bears the weight of the body. It is subject to significant stress. This joint includes three forms of movement: dorsiflexion and plantarflexion, eversion and inversion, adduction and abduction. The instep and upper form a right angle when in normal condition. As the toe moves downward, the angle between the shank and the instep gradually increases, which is plantar flexion. The opposite movement is the dorsiflexion. Eversion is assisted by dorsiflexion, while inversion is assisted by plantar flexion. The outward

rotation of the foot around the shaft is known as abduction, and the opposite movement is known as adduction

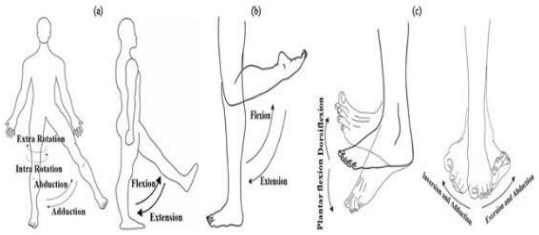


Fig. 1 Movements of lower limb joints:(a)hip,(b)knee,(c)ankle.

3. LOWER LIMBS INJURIES

The lower limbs in human bodies are responsible for locomotion, allowing movement support and shifting from place to place by walking. Many disorders are likely to affect the motor skills of the lower limbs and lead to gait abnormalities or instability. Among the injuries of the lower limbs are:

Disorders of the speaking apparatus mainly concern athletes and are due to excessive or unusual solicitation of the lower limbs [2]. Among these disorders, pathologies are evolving, such as hip osteoarthritis and knee osteoarthritis, as there are injuries such as tendonitis ligament injuries, meniscus injuries, patella fractures, etc.

Among neurological damage are spinal cord compression or injury, lack of coordination of movements and loss of balance, damage to peripheral nerves, and pathologies linked to cerebral accidents such as cerebrovascular accidents, Multiple Sclerosis, etc.

4. STATE OF THE ART OF REEDUCATION ROBOTS OF LOWER LIMBS

Kaczmarski et al. [3] in 2011,developed“REHABILITATION ROBOT RRH1.”
a prototype rehabilitation robot for the lower limbs with five active degrees of freedom (5DOF). The generation of the movement is done according to the trajectories programmed by the physiotherapist. The presented prototype of the rehabilitation robot can provide different training exercises, such as flexion/extension of the hip and knee and abduction/ adduction of the leg in complete patient safety. The robot consists of an aluminium frame and an adjustable column located on a rectangular base and brakes, while its height can be adjusted for a bed and a patient by the crank. The RRH1 rehabilitation robot is equipped with several safety systems, continuous position monitoring of the speed and strength of each joint, and a rotary potentiometer for the absolute measurement of the position of the joint. This prototype can be used safely for conscious and unconscious patients at the beginning of rehabilitation. It can also be used for daily leg exercises for patients in long-term beds or intensive care. RRH1 offers a more compact construction and better mobility than a wire robot.

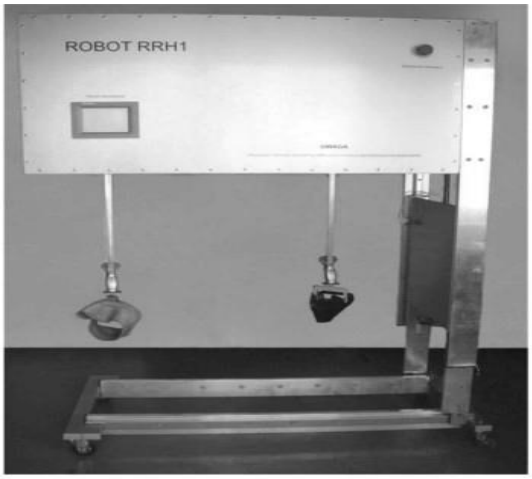


Fig.2 RRH1 ROBOT REHABILITATION.

EM Bouhabba et al. [4] 2013 proposed a lower limb rehabilitation robot to help people with paralysis caused by a disease or a movement disorder of the lower limbs following an accident to improve and regain limb functions. LLRD is characterized by providing 03 degrees of freedom, allowing movement of the hip, knee and ankle joint inthe sagittal plane. The rehabilitation training modes are active, passive, and assisted, whose control methods are current control, speed and position control, and current control based on signal and torque feedback from EMG, respectively. The LLRD monitoring system is represented by wearable sensors controlling knee and ankle motion motors and an IPMC sensor mounted on the surface of an upper limb to monitor knee flexion and extension. The main contribution of LLRD is the development ofa practical model of IPMC sensor, which iseasily applicable to the real world. Another contribution is that the performance of the IPMC sensor is demonstrated in an

actualbiomedical application for lower limb robots.

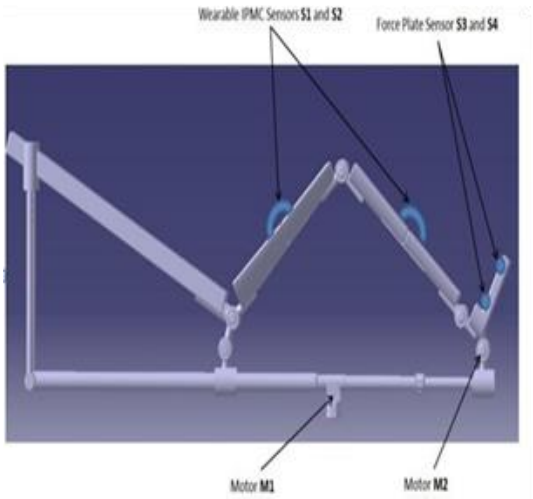


Fig.3 Lower-Limb Rehabilitation Robot Design.

Serdar and Erhan [5] developed a 1DOF knee rehabilitation robot, established by the therapist, capable of performing passive, active, and resistive rehabilitation exercises. When the physiotherapist performs the movements necessary for the patient, the system records the forces applied to the patient by associating them with position and time data. After the procedure, the system uses the data entered through the user interface to have the patient perform movements automatically. The robot contains a connected servo motor that measures the force applied to the patient. Proximity sensors limit the robot's movements for safety reasons. In addition, a corrugated structure metal member is added to the motion-limiting mechanism of the manipulator robot. It also contains an emergency button on the control panel in case of emergency. The control of the manipulator is based on impedance control techniques. In the next study, the exercises will be modeled usingthe controller and the system will be tested on healthy subjects.

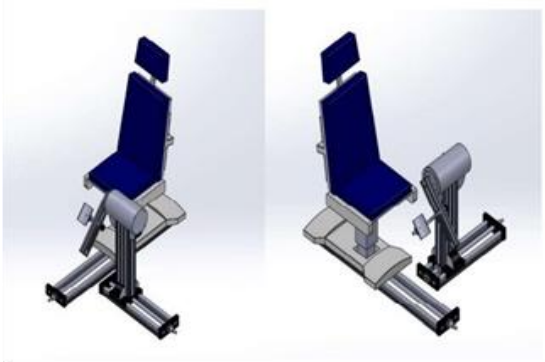


Fig.4 A low-cost knee rehabilitation robot for therapeutic exercises

Calin et al. [6] produced a stationary parallel robotic training system to rehabilitate patients' lower limbs in the acute post-stroke phase. The robotic system comprises two modules: one dedicated to hip-knee movements and the second dedicated to ankle rehabilitation. The robotic modules are interconnected to allow the three joint rehabilitation exercises to be performed simultaneously (if necessary). RAISE's architecture provides four degrees of freedom (4DOF), allowing knee and hip (flexion/extension) and ankle (planetary flexion/ dorsiflexion, inversion/eversion) rehabilitation exercises. The robot's structure is supported by a frame at the end of the therapeutic bed, where the patient's leg is placed along the robotic system, and the foot is fixed to the frame. Future research aims to develop a raise for several complex therapeutic exercises such as walking.



Fig.5TheRAISEroboticsystem.

Heriano et al. [7], in 2019, did a study to design and manufacture a knee-focused lower limb rehabilitation robot. The design of the rehabilitation robot should be flexible so

that it can be used independently. This robot trains flexion/extension movements of the patient's knee after a stroke. The training exercises can be done flexibly and compactly in a lying or sitting position. For the control of the robot, they used a PWM potentiometer, which adapts to the patient and an Arduino mega 2560 for data retrieval. The results of the tests carried out on the patients indicate that the rehabilitation robot works well

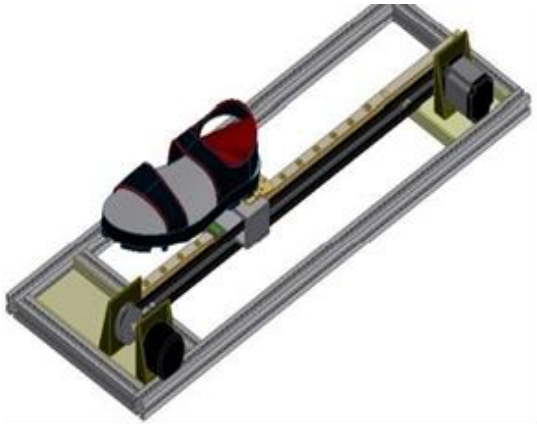


Fig . 6 Post-stroke rehabilitation robot for knee.

MKAB Ismail et al. [8] from the University of Perlis. Aran. In Jan 2021, Malaysia developed 02 degrees of freedom rehabilitation robots for people with disabilities and those with lower body motor impairment, mainly focusing on ankle rehabilitation. PBARR is an economical robot with a simple structure that allows users to perform exercises regularly at home without consulting the therapist. This prototype contains 04 stepper motors that will enable the forward rotation of the platform, performing ankle rehabilitation represented by dorsiflexion/ planflexion and inversion/eversion, respectively. PARR is manufactured for different foot sizes and ideal weight (5kg). The stepper motors do not reach the maximum movement.

Wang et al. [9], in 2019, proposed " Design and analysis of spatial four-DOF multi-pose lower limb rehabilitation robot", a lower limb rehabilitation robot dedicated to subjects with significant lower limb weakness. This 4DOF robot offers 2DOF in the hip, 1DOF in the knee and 1DOF in the leg, the training exercises are performed in different postures; sitting, lying or standing. This robot has a parallel series hybrid mechanism, whose joint movement of the hip is parallel, and that of the knee and peg is in series. Restoration of the lower limbs can be done pleasantly by the joint torque sensor and foot and leg weight sensor, which can anticipate human lower limb movement purpose. In the future, the work will be based on implementing the restaurant robot control to meet the comfort needs of various patients.



Fig. 7 Parallel Ankle Rehabilitation Robot.



Fig. 8 spatial four-DOF multi-pose lower limb rehabilitation robot.

Luo et al. [10] from Shenzhen University, Guangdong, China, in 2021, "Development of a New Lower Limb Rehabilitation Robot for Bedside Training", proposes a simple, reliable and easy-to-use lower limb rehabilitation training robot based on movement characteristics of the human lower limbs. The robot mainly comprises a cart, an electric column, and a left and right drive mechanism. It also allows the treatment process to be optimized according to the force conditions collected by pressure sensors placed on the pedals. The therapist pushes the robot attached to the end of the bed, and the patient's foot is placed on the

pedal via a strap. The robot provides rehabilitation movements of the hip, knee and ankle in the sagittal plane in two training modes: active and passive. This rehabilitation robot compensated for the shortcomings of existing training devices and solved the problems of bedridden stroke patients in getting practical training. Future work will refine the structural design and control system.

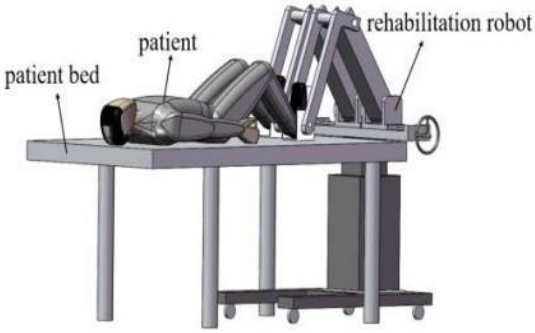


Fig. 9 A New Lower Limb Rehabilitation Robot for Bedside Training.

Yupeng et al. [11], in 2022, designed "Design and Experimental Research of 3- RRS Parallel Ankle Rehabilitation Robot», a parallel ankle rehabilitation robot that works in two types of simple and compound training. The 3-RRS PARR has three degrees of freedom (3DOF) of ankle rotation, and its centre of rotation is fixed in space. This robot mainly consists of a static platform and a mobile platform connected by three chains of branches. The ends of the chains are connected to the mobile platform by a spherical joint. Because of the robot's structure, the centre of rotation can coincide with the patient's ankle joint during the rehabilitation training. The 3-RRS PARR ensures patient safety in the rehabilitation process, avoids secondary injuries and offers high human- machinecompatibility. The manipulator is driven by a low-speed torque motor, an adjustable pedal installed on the moving platform, and an encoder installed on the motor monitors the movement data of the crankshafts. It is controlled by a PI (speed regulation) corrector and a P corrector (position regulation). The feasibility of the proposed 3-RRS PARR has been proven, and the foundation for human-machine experiments has been laid. Regarding the existing research on ankle rehabilitation robots, comfort during rehabilitation is an urgent issue to address. In follow-up research, structural improvement and kinetic analysis of PARR will be done to improve human-machine compatibility further. Other experiences are an adjustable pedal installed on the mobile platform and an encoder installed on the motor to monitor the movement data of the crankshafts.

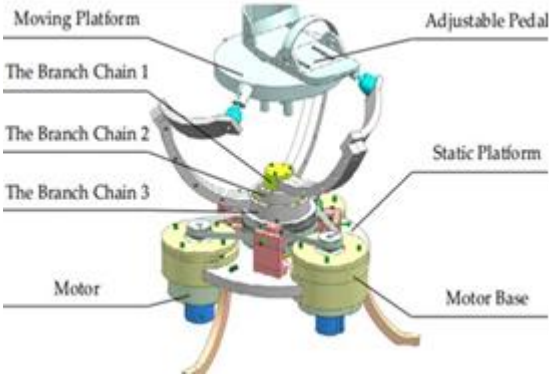


Fig .10 3-RRS Parallel Ankle Rehabilitation Robot.

Martinez et al. [12] 2022 proposed the design of a 01 degree of freedom (DOF) lower limb rehabilitation system based on knee flexion/extension movement in the sedated position. This system performs up and down movements, causing the knee'stretch and contract. In addition,t he mechanism can also perform hip and ankle rehabilitation. The digital system simulation uses a program such as the Working Model. With these programs, a four-bar mechanism is selected, which offers a practical and straightforward solution to reproduce the movement for knee flexion-extension rehabilitation. The result shows a mechanism with an isokinetic motion that indicates an unstable behaviour within the simulated mechanism, establishing a system of damping in which intelligent shock absorbers can stabilize this decrease in the mechanism. With this damper, this problem can counteract and resist angular acceleration variations in the system.

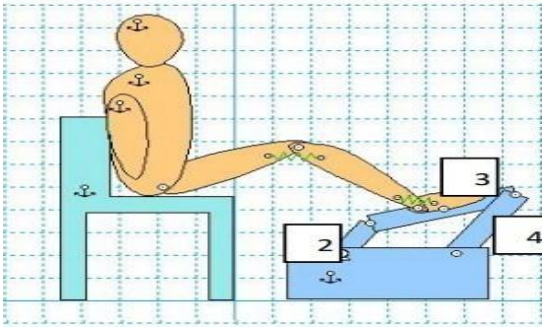


Fig.11. Simplified mechanical system for knee rehabilitation.

Voloshkin et al. [13] proposed a CPM (continuous passive motion) robotic system for treating the patient's lower limbs with generally uncontrolled limbs. The robotic system consists of a mobile platform where the patient's foot is fixed, and a series 03-RRRR active manipulator used as a passive orthosis to support the patient's lower limb fixed on an adjustable chair. The robotic system provides the necessary effort for rehabilitation, which data from the controller, encoders, muscle activity sensors and the lever mechanism must control. Experimentally, it's essential to install elastic elements of various stiffness and hydraulic cylinders with individual anti-return chalets to refine the rigidity.

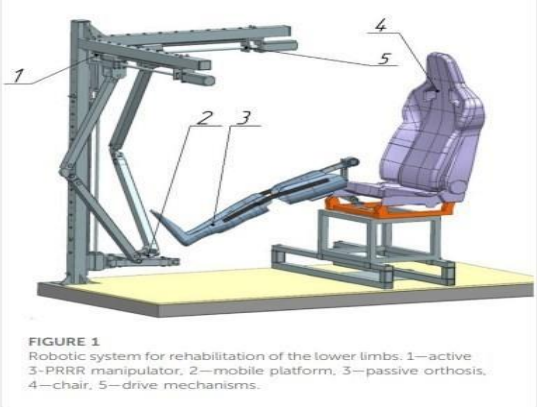


Fig.12. Design of Suspension Lever Mechanism Biomedical Robotic System.

In [14], the authors designed LOBO, a new type of lower limb rehabilitation robot to meet stroke subjects' rehabilitation needs, such as applying muscle strength training for older people to fight against the effects of ageing. LOBO is designed based on 2-PRR parallel mechanism, its structure provides 3DDL to the lower limb, represented respectively by ankle dorsiflexion/plantar flexion, knee joint flexion/extension and hip

joint flexion/extension in the plane sagittal. The overall structure of LOBO comprises a frame, lift seat, and lower limb rehabilitation training components; the rehabilitation training set includes a motor, linear stage, rotation vice module, square tube, and pedal component. LOBO was used in the experiment to evaluate a proposed pattern generation method that consists of a relay board and four actuators. The robot uses a proportional differential corrector (PD) to control the rehabilitation movement. To verify the advantage of the feasibility of the proposed mechanism, experiments are conducted with three volunteers.

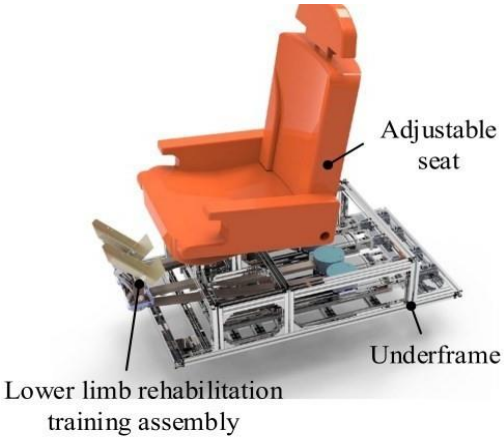


Fig.13. Structure of LOBO.

Table1, illustrates the safety precautions of each robot.

Joint	Plan	Movement	Amplitudesphysiological
Hip	Sagittal	Bendingextension	110°-120° 10°-15°
	frontal	Adduction Abduction	15°-25° 45°
	horizontal	Spininternal. Spinexternal	30°-45° 40°-60°
Knee	sagittal	BendingExtension	Max-160° 0°
	horizontal	Spininternal. Spinexternal	20°-30° 30°-40°
ankle	Sagittal	Dorsiflexion Bendingplantar	20°-30° 30°-40°
	frontal	Adductionabduction	0°-35° 0°-25°
	horizontal	Eversioninversion	10° 25°

5. ISSUES

The motion range of the lower limb is a fundamental part of human movement. It can be affected by injury, accident, pathology or surgery, the consequence of which is restriction of the affected joint or reduced range of motion. It is very often difficult to restore the previous joint situation; the restoration of normal movement of the limb or

Table 1 Safety precautions of each robot.

Device	researchers	Functionsalteredtargeted	Numberof Freedomsprovided	Calcificationtherapy	SafetyPrecautions
ROBOTREHABILITATION RRH1	Marcin andGrzegorz	Leg, knee ,hip	5DOF	assisted	Immediate engine shutdown in an emergency, Stopping the software in any phase of the learning execution algorithm, Continuous monitoring of the position, speed and strength of each joint, Immediate shut down when a malfunction occurs.
Lower Limb Rehabilitation Robot Design	EM. Bouhebba andal	Leg, knee ,hip	3DDL	Assetpassivassisted	IPMC sensor was mounted on the surface of an upper limb to monitor knee flexion and extension Position, velocity and current control based on EMG data
DevelopmentofaLow-Cost Knee RehabilitationRobotforTherapeuticExercises	Serdar andErhan	Knee	1DOF	Asset,passive, resistive	The therapist encourages the patient to perform the exercises with the robot Impedance control based on force and position.
RAISE	Calvinetal	Kne, Ankl ,Hip	4DDL	Coaching stationary	The patient's limb is kept as ergonomically positioned as possible to ensure proper rehabilitation without damaging the patient's joints
Post-strokerehabilitationrobot for knee: a compactdesignandmanufacture	Herianoetal	Knee	1DOF	Passive	The operator controls the robot movement on the control panel Motor speed control is by potentiometer in the form of PWM
Designandanalysisofspitianfour-DOFmulti-poselowerlimbrehabilitationrobot	HongboWangetal	Hip Knee Ankle	4DDL	Passive	Articular torque and weight sensors
Parallel AnkleRehabilitation Robot	MKABIsmailetal	ankle	2DDL	asset	4 stepper motors used to measure and track the angle of the platform during rehabilitation. A setting in the programming software to make the platform move smoothly at a certain angle.
ANewLowerLimbRehabilitationRobotforBedsideTraining	Chengkai Luoetal	Ankle, Knee, Hip	4DDL	Asset, Passive	Pressuresensorscollectforceconductions
Design and ExperimentalResearchof 3-RRSParallel AnkeleRehabilitationRobot	Yupengetal	Ankle	3DDL	Passive	PI controlsspeed, Pcontrolsposition An encoder was used to measure the rotationof the motor The adjustable pedal has beenremoved to monitor the corner of the platformmovementbytheanglesensor the patient's ankle joint coincides with thecenter of rotation to ensure patient safetyduringrehabilitation.
Simplified mechanical systemforkneerehabilitation	J.MendozaMartinezetal	Knee	1DOF	passive	Establishmentofadampersystem(intelligentdampers) tostabilizethe mechanism.
DesignofSuspensionLeverMechanism BiomedicalRoboticSystem	A. Voloshkinand there	Memberlower		asset	Elastic elements are installed on each side ofthe orthosis to reduce the rigidity of the elasticelements(reducedby2times) themaximumstrengthofthepatient'slimbis <=70N
MechanismDesignandPerformance Analyzer ofaSitting/LyingLowerLimb Rehabilitation Robot	Fangynetal	Ankle Knee Hip	3DDL	asset	The robot uses a control path tracking (PD)methodtoimplementthesimulatedrehabilitation movement,The robot contains 4actuators.

joint depends on the exercises led by the physiotherapist; in turn, physiotherapy focuses on the new robot technology to carry out the patient's treatment process. So: Can robot-assisted therapy optimize joint mobility of weakened lower limbs in patient safety?
To ensure that the patient is not accidentally injured during rehabilitation processes, the limb's range of motion must be strictly limited to the maximum angle of movement of this joint. Normal physiological ranges of motion have been documented in the literature and are well-known in clinical practice. The following table shows the physiological human lower limbs[15.16]:

To solve this problem, the devices used must contain joint range of motion measurement systems so as not to exceed the physiological range of motion and ensure patient safety without causing additional damage. Among the motion measurement systems used are the following:

- Goniometers: are potentiometers specially assigned to the measurement of joint angles. They are also essential for monitoring the progress of recovery during the patient's rehabilitation. The goniometer comprises two arms: one is fixed to one of the segments of the joint, and the other to the second. The potentiometer returns an electrical signal proportional to the value of the angle between the two arms. The potentiometer used must obviously vary linearly with the angle.

-The accelerometer is an inertial sensor aimed at measuring the accelerations of the limb on which it is positioned. These are usually strain gauges that measure the force related to acceleration. This type of sensor does not present any major difficulty in use. A preliminary remark which is important for a correct treatment of the data, is that the acceleration is measured in the frame of reference of the sensor. Consequently, it is essential to know, at all times, the position of the frame of reference.

-Force Platform: is the equipment widely used in motion analysis. It makes it possible to record the contact forces during support on the ground and to understand the relationship that exists between these measurements and the movement of the body expressed in terms of linear acceleration or speed of the global center of gravity of this body and from the global angular momentum expressed also to the global gravity [17]. Therefore, the platform must replace the ground and be integral with the latter on which it is anchored. EMG or biofeedback is the most widely used measuring instrument for measuring muscular effort. It consists of two electrodes glued to the skin. The EMG signal is very rich information because it not only carries movement information, but also contains information on the stiffness of the limbs or the state of muscle fatigue. The signals obtained by this method under different conditions make it possible to establish relationships between the electrical phenomena measured and the nervous and muscular, voluntary and reflex activity. Electromyography can be considered common in the field of physiotherapy, EMG measures muscle activity related to walking or other movements. In dynamic simulations, EMG signals are used to indicate muscle strength levels[18], that is to say an increase in muscle strength which corresponds to an activation in the EMG signals. This information is used to qualitatively validate musculoskeletal models in biomechanical simulations.

6. Conclusion

Rehabilitation technology is a promising solution for developing rehabilitative training devices, helping people with neurological, handicapped, or accidental problems…..to restore their motor functions and recover or compensate for the loss of movement of a limb. or a joint and give them the ability to complete the most basic life. In this work, we presented the state of current research on lower limb rehabilitation robots based on different training modes, safety precautions and joint amplitude measurement systems. There is still a great lack of research regarding lower limb rehabilitation robots. Future research into rehabilitation robots should focus on the following points:

1.The systems design capable of being adapted to the physiological conditions of patients, comfortable, accurate, high load capacity and allowing the development of exercises (passive, active) under minimal supervision of physiotherapists.

2.Safety issue, safety is the key to rehabilitation robot design. This requires a structural and software design of the robot that conforms to human movements, to prevent the occurrence of injuries and damages.

3.Control; Due to the individual difference of patients, the robot must perceive the necessary state information for the patient's movement, adopt the corresponding control strategy.

4.Development of cost-effective, easy-to-move devices to meet the needs of all patients.

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