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LOKOIRAN- A Novel Robot for Rehabilitation of Spinal Cord Injury and Stroke Patients

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Abstract—**This paper will focus on the design and development of a new gait training robotic device (LOKOIRAN) for patients with balance and locomotion disorders. The process of rehabilitation in this system is based on partial weight bearing system and programmable foot-plate training. The system consisted of several subsystems following: Driving and transmission system, back supporting system, leg exoskeleton, body weight support system and control system. A virtual reality environment was also designed and integrated to the system in order to motivate patients during rehabilitation protocol. The experimental tests on healthy subjects were performed to evaluate the performances of mechanical and electrical subsystems of LOKOIRAN robotic system. The newly developed device has several advantages in comparison with similar commercial systems. Firstly, the physical improvements of patients are expected to increase due to synchronized and functional movements of upper and lower limbs. Secondly, special leg exoskeleton and back supporting system were designed to increase the stability and balance of subjects. Although the aforementioned robotic gait device is well suitable for patients with SCI and stroke, it could be used for MS patients, sport injury cases, aging and people with stability and balance disorders.**

Index Terms:—**Gait training device, Body weight support system, Exoskeleton, Rehabilitation.**

I. Introduction

According to W. H. O. report, about 14% of people in the world suffer from a kind of disabilities [1]. The main causes of disabilities are stroke, spinal cord injuries, trauma, accidents, sport injuries, MS, aging, and natural disasters [2]. These conditions might cause disabilities and lead to motor and balance dysfunctions. Therefore, a large number of patients need rehabilitation services including locomotion and gait training in order to improve their abilities and quality of life.

The traditional gait training in these conditions is mostly based on motorized treadmill, body weight supporting system and at least, two therapists were required to supervise, monitor and help movements [3]. In addition, rehabilitation services for pathologies such as SCI and stroke will last 6 months to 2 years and in many circumstances could be needed for life time. Moreover, gait training and assessment systems are sophisticated, time consuming, expensive. Therefore, many rehabilitation centers could not afford to prepare these sophisticated systems.

Accordingly, many researches have focused on the design and development of intelligent and automated robot devices to improve the efficiency of therapy. These new systems have considerably reduced the therapist's endeavor and increased the duration of training sessions. Finally, the level of motor recovery could be assessed by quantitative measurements of the force and movement patterns by these robotic devices [4, 5].

Recently, robotic devices have been developed to reduce the therapists' labor; among them, Lokomat is the most clinically evaluated device [5]. It consisted of a robotic Orthotsis, actuated at hip and knee joints and free in ankle joint. The drives Movements are precisely synchronized with the speed of treadmill. A mechatronic body weight support system is also integrated in the system [6].

Lokohelp is another commercialized gait rehabilitation device; there is no Orthosis for training with exception of a pre defined specified feet path [7].

The Active Leg Exoskeleton (ALEX) is a powered leg Orthosis for motor-impaired patient. The devise is designed to supply controllable torque to hip and knee joints. The current control strategy is based on the assist-as-need. They have shown that the gait pattern of patients were improved and became closer to healthy subject pattern [8]. They have also redesigned a new device called ALEXII, in which some DOF's added. They have compared and discussed the effects of number of DOF on the gait improvement [9].

LOPES is another successful gait rehabilitation device based on series elastic actuators. The series elastic actuators are back-drivable and easy to control. Another feather of these actuators is that the angular position sensors can be used instead of torque sensors [10]. There are some other devises

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based on the treadmill in the literature as ReoAmbulator [11] and RGR [12].

Foot-plate training devices are among a category of rehabilitation system that the patient's feet are moved with two programmable plates and the weight is partially supported. GT1 is the only commercialized gait trainer in this class [3]. The vertical and horizontal movement of the mass center is controlled by the rope (support the patient form the top). They have shown that a non-ambulatory hemiparetic subject needs a little help of therapist on the gait trainer, while two therapists were required to support treadmill walking.

Haptic walker is more advanced than GT1 and can simulate not only the floor walking but also foot motions like sliding, stumbling, climbing stairs and walking on rough surfaces [13, 14]. In addition, the programmable foot-plate, is capable to set the cadence and stride length for each subject.

A 6-DOF rehabilitation device is capable to update velocity of walking with upper and lower limb connections [15]. This robot is composed of an upper limb set, a sliding set, two footpad sets, and a body support system. The footpad set of the sliding part generates 3-DOF spatial motions of the sagittal plane for each foot. A group of researchers in Rutgers University has made a system with two footplates each on the top of two Stewart robot [16]. This system had some points, first, the workspace and dynamic range of this mechanism is limited and do not allow the walking profile. Second, the number of DOF is too much. There are also some other activities in this classification like Gait Master5 (GM5) [17] and LLRR.

In this project, a new lower-extremity rehabilitation robot (LOKOIRAN) has been proposed. This system is based on motorized feet-plate training and a mechanized body weight support system that was designed and developed under the supervision of the Brain & Spinal Injury Research center (BASIR) of Imam-Khomeini Hospital. Unlike other devices, GT1 and Haptic Walker, a passive Orthosis was designed to fully support the patient and provide the joint angle data during training. So, just one therapist is needed to monitor and supervise the training with minimum effort. Another significant difference between this system and other similar gait training systems is the synchronized movement of the lower and upper extremities which has a significant effect on the improvements of subjects. Finally, the virtual reality environments are integrated the system in order to motivate the subjects for rehabilitation.

In the followings (section I and II) the subsystems of device will be introduced and in section III, the suspension system will be overviewed. The back supporting system and the passive leg exoskeleton will be explained in section IV and the virtual reality environment will be described in section V. Finally, in section VI, the conclusion will be presented.

II. System Description

A. Subsystems Overview

The LOKOIRAN rehabilitation robot is consisted of following subsystems (Figure 1), Structure, Driving system, Body weight support system, Back supporting and Leg exoskeleton, Virtual reality and Graphical user interface.

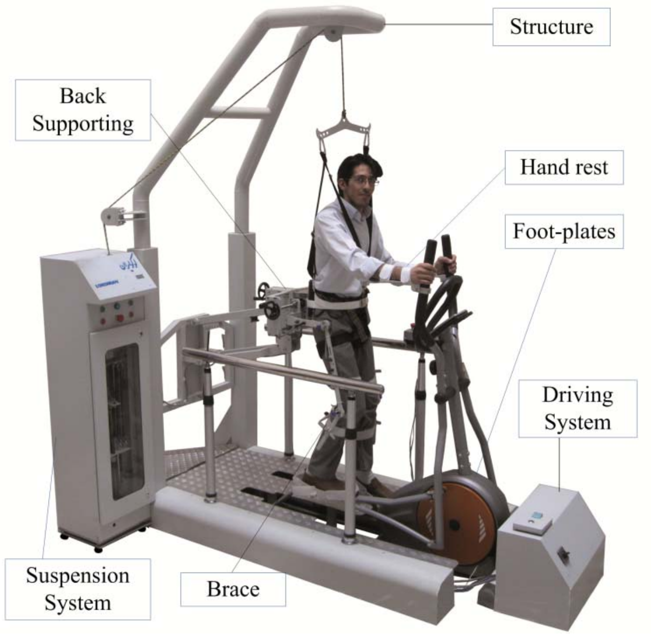

Fig. 1 The LOKOIRAN rehabilitation robot and the subsystems of the device

B. Structure

The structure of the robot is consisted of lower and the upper platforms. The upper platform supports the subject's weight with more than 135kg by 2.7 safety factor. The oscillation of the person during training will cause a vibratory force on the structure; therefore, the upper platform is designed to have the minimum displacement and vibration. The lower platform has two adjustable parallel handles on the side of the subject. These parallel handles are useful for subjects who are able to use their hands. The other characteristic of this system is that the structure can be dissembled conveniently. On the other hand, the prismatic joint is inserted among two column of the upper platform which permits easy disassembling in transport. Finally, embedding a ramp at the end of the lower platform, the subject is able to enter to the platform using a wheelchair.

C. Driving System

The driving system is consisted of an AC motor connected to a slider-crank mechanism via belt and pulleys. The motor is derived with an inverter. The inverter changes the input voltage frequency from 0 to 60Hz with 0.01Hz resolution. The speed of motor has linear correlation with input frequency. The inverter is connected to the computer via RS-485 serial connection and required parameters could be adjusted during training.

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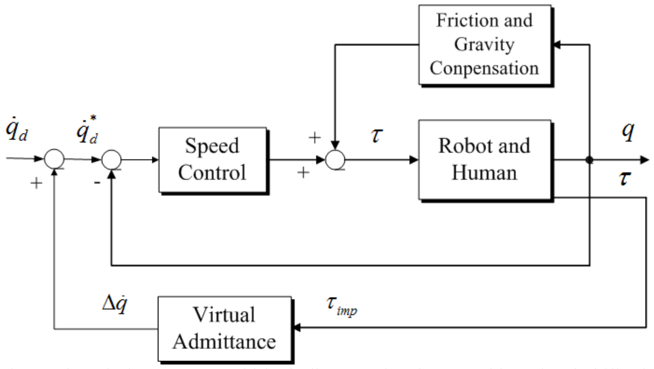

Fig. 2 The admittance control block diagram, implemented in gait rehabilitation device (LOKOIRAN)

D. Control System

The control system has two modes, the speed control mode and admittance control mode. In speed control mode, the angular velocity of the slider-crank mechanism and the walking speed could be maintained at desirable parameter. The speed is adjusted according to the therapist experience and the condition of subject from 0 to 3.3 km/h. The advance sensor less vector control integrated in the inverter to control the angular speed of the motor. The accuracy of the speed control is 0.5% of maximum speed.

In admittance control mode, the torque feedback of the motor is used to form an outer loop in control block diagram as shown in Fig. 2. The outer loop produces a reference speed for inner loop. The inner loop is the fast speed control described in the first mode. The admittance controller allows the subject to change the reference speed according to his/her strength. On the other hand, if the subject fails to follow the prescribed speed, the system permits him/her to reduce the speed and if the subject follows the device and also produce a positive torque, the speed will increase. The data frequency of outer loop is 20Hz.

D. Graphical User Interface

A graphical user interface is designed to enter the commands and observe the outputs. The torque and power graph, the knee extension/flexion and hip extension/flexion are shown online on the screen. The distance and time of the training section, reference speed, and control mode could also be adjusted. Finally, it is possible to save all data of the session.

E. Other Subsystems

The suspension system is designed to compensate the weight subject in partial manner and therefore, is able to elevate the subject from sitting to standing position (refer to section III).

In addition, special hand rests are designed to keep the hand of subject connected to the device. Hence, the improvement will be increased due to the synchronization between upper and lower limb movements.

The back supporting system will support the trunk and permits the body to oscillate freely during walking while the back of the person is always in the upright position. The leg exoskeleton are specially designed to constrain the leg movement in the sagittal plane and to improve the balance. Furthermore, data of joint movements could be collected (refer to section IV).

The virtual reality as a motivating environment could be shown on the screen in front of the subject during training. The detailed features will be described in section V.

III. Body Weight Support System

A. Introduction

Partial body weight support (BWS) is one of the most effective rehabilitation methods for gait training in a vast range of patients [18]. Paralysis of the leg muscles often prevents patients from supporting their own body weight during stance phase. Reducing the gravitational forces acting on the legs by a BWS system would facilitate stepping movements. In addition, the BWS system ensures safety and stability of the subject walking on treadmill [6]. The body weight unloading is adjusted according to the strengths and ability of subject. However, it could usually be set from zero to 100 percent of body weight and adjusted during the training sections.

B. Types of BWS systems

So far, four types of BWS systems have been introduced as followings: Static, passive counter weight, passive elastic and active dynamic system. In static BWS, the weight of the subject is supported by a passive or automated winch. Since no suspension is in this method, the subject feels uncomfortable and therefore, the quality of rehabilitation might be deteriorated. In passive counter weight method, the inertia forces causes deviation of the suspension forces from desired value [6]. In addition, the amount of unloading cannot be adjusted continuously. In active dynamic BWS, a force sensor provides the feedback to the control system and the controller produces the actuator input to keep the suspension force constant.

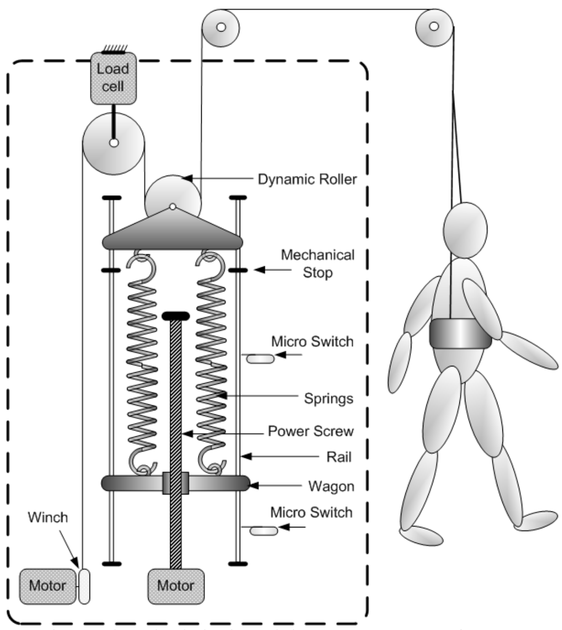

Fig. 3 The passive elastic body weight support system of LOKOIRAN

The active dynamic type of BWS is more complicated than the previous types. Also researches [14] has shown no significant difference in comparison with other system particularly with passive elastic system. So, a passive elastic system was designed in this project.

C. BWS system Description

The body weight support system has three requirements:

1. Elevating the subject from sitting to standing and vice versa
2. Adjust the amount of unloading weight in a continuous manner.
3. Keep the unloaded weight constant as much as possible
4. Provide safety during training

A passive elastic BWS system was designed and has been shown in Fig. 3. The lower ends of the springs are attached to a wagon; the elevation of wagon is changed via a geared-motor and a power screw. The wagon slides on two parallel rails and two micro-switches that limit range of motion. The upper ends of the springs are attached to a dynamic roller sliding on two parallel rails. The motion of dynamic roller is constrained between two mechanical stops. The pretension of the springs is adjusted by changing the elevation of the wagon. Another motor-winch is used to change the elevation of the subject.

There are five steps in adjusting the system for an individual. Consider an 80kg person and the amount of unloading is 50kg of weight:

Step1: adjust the pretension of the springs via motor and power screw. The pretension has to be $50g / K_{spring}$ Newton. Note that the dynamic roller will bop to the lower mechanical stop in this step and will never dispart until 50kg force is applied to the rope

Step2: fasten the harness to the subjects whilst he/she enter with wheelchair through the ramp.

Step3: lift the subject and suspend him/her using the winch-motor. At this time, the dynamic roller bop to the upper mechanical and stop.

Step4: gradually lower the subject until the dynamic roller separate from the upper stop.

Step 5: fasten the Exoskeleton (orthotic device) to the legs.

Step6: System Start so the footplate begins a repetitive motion. Now the dynamic roller oscillates and provides a soft suspension while suspension force is approximately 50kg.

The constructed body weight support system is shown in Fig. 4. A 250w DC motor is coupled to a 1:25 worm gearbox and the power screw with 4 mm pitch is connected to the output of the gearbox. The average output speed of the wagon is 0.5 cm/s. The springs have the equivalent stiffness of 3900 N/m and can be stretched up to 40 cm. So the maximum unloading weight is 80kg.

The second motor is a direct drive motor and connected to a 1:80 worm gearbox and the output is coupled to a winch. The average speed of the rope is 3.3 cm/s. Since the transmission ratio of the gearbox is high and the system is self locking. Therefore, the rope is locked when the motor is off.

Finally, the tension force of the cable is measured by a S-shape load cell and displayed in a 7-segment indicator.

Fig 4. The body weight support system constructed for LOKOIRAN rehabilitation device

IV. BACK SUPPORTING SYSTEM AND EXOSKELETON

A. Introduction

One of the main differences between proposed and similar devices [3, 14] the supporting systems. According to clinical trial rehabilitation, the patient should be supported as much as possible. Increasing the level of freedom in SCI and stroke patients causes problem in spastic situation. The level of freedom of robotic exoskeleton has been studied in [9].

In proposed device, the body is constrained to move in sagittal plane and four degree of freedom is considered to be adjusted for each person.

B. Back Supporting System

The back supporting system has a four-bar mechanism attached to the back of the patient and allows free vertical oscillation of the back and pelvis. The weight of the 4 bar linkage is compensated by a gas spring shown in Fig. 5. The gas spring has 600N capacity. Another advantage of 4 bar mechanism is that the system can goes to the vertical situation and let the patient enter into the device.

The pelvic width might be adjusted by a revolving handles from two sides. A ball screw transforms the rotational motion into linear motion with low friction, high accuracy and self locking property. The back horizontal position can be adjusted for patients with different sizes (see Fig. 5). The therapist set the back position so that the patient is perfectly erect.

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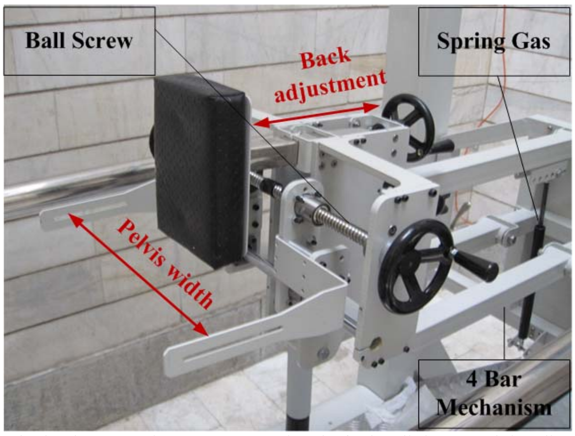

Fig. 5 The back supporting system consisted of 4 bar linkage, pelvis adjustment and back adjustment

C. Leg Exoskeleton

The main parts of the leg exoskeleton are shown in Fig. 6. The whole structure of the leg exoskeleton is made of aluminum and each leg has 3.5kg mass.

Each leg has 3-dof, hip abduction/adduction, hip flexion/extension and knee flexion/extension. The hip abduction/adduction should be adjusted before training while the other degrees of freedom are free. Table I shows the specification of the whole system.

The range of motion of knee and hip in sagittal plane could be limited. On the other hand, two adjustable mechanical stop for each joint is inserted. The thigh length could also be set discretely as indicated in Fig. 6. A spring-return key is designed for ease of use.

Three cuffs are designed for each leg, above and bottom of the knee joint and one above the ankle joint. The lateral and ventral position of the cuffs could be adjusted continuously. In this method, the subject is perfectly constrained and the safety is guaranteed. The cuffs are made of compressed plastic (ABS) which is a light and flexible material and protects the wearer from skin abrasion.

The Knee and hip joint angles in sagittal plane are measured by potentiometers. The potentiometers have 5% accuracy and acceptable linearity. The joint angle data are being transferred to PC and plotted on the screen online.

TABLE I. THE DEGREE OF FREEDOM SPECIFICATIONS

Degrees of freedom	***Range***	***Step***	***Free/Adjustable***
Hip extension/flexion	-60˚ - 80˚	Continuous	Free
Knee flexion/extension	0 - 60˚	Continuous	Free
Hip abduction/adduction	-20˚ - 20˚	Continuous	Adjustable
Thigh length	37 - 49cm	Continuous	Adjustable
Pelvis widths	20 – 37cm	Continuous	Adjustable
Back adjustment	24 -32cm	Continuous	Adjustable
Hip and knee ROM	In steps of 20˚	Discrete	Adjustable
Cuff lateral position	0 – 8cm	Continuous	Adjustable
Cuff ventral/dorsal position	0 – 14cm	Continuous	Fixed

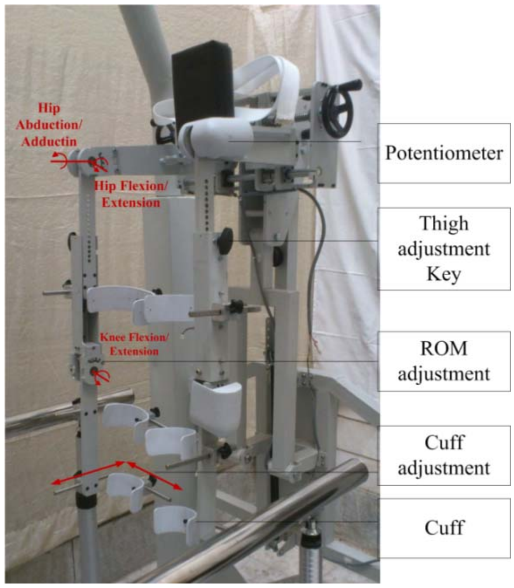

Fig. 6 The leg exoskeleton supporting the lower-extremity and has 3-dof for each leg

V. VIRTUAL REALITY

Virtual Reality is computer-simulated environment that simulate the real environment in imaginary worlds. The virtual environment is displayed on a computer screen and additional sensors and feedbacks are required to help the person for feeling the real world.

Recently, Virtual Reality (VR) has become a lively topic to debate. Several attempts have been made to show the effectiveness of VR in treatment of disease.

In the present robotic device, two virtual reality environments are designed to motivate the subject. The first one is an urban environment; an avatar is walking on the pedestrian while the trees are on the left and buildings are on the right. The speed of character is dependent on the subject effort.

In the second environment, model of Naghshe Jahan Sq. (famous Sq. in Esfahan) is built in 3D-max software(Fig. 7a) The model is then imported into Virtool software to animate the character in real-time. Five different paths are considered in the 160×500 meter environment. Only sensory information that could change the speed of character is the torque of main motor. If torque increase, it means that the subject is not following the robot perfectly so the speed of the character must be decreased and vice versa.

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Fig. 7 The virtual reality environments. a) Naghshe-Jahan sq. in Esfahan (top) b) a modern city environment (bottom)

VI. CONCLUSIONS

Robotic rehabilitation could improve the locomotion and balance in a vast group of pathological conditions. It could generate a repetitive, constant and yet controllable pattern of movements. Furthermore, it could prevent the possible injuries to physical therapists. In this article, a new robotic gait training devise was introduced. The control system provides flexibility in motion and permit subjects to change the speed of the foot-plates. Also, the back and leg exoskeleton and a novel suspension system for rehabilitation of lower limbs were introduced in term of synchronized movements of upper and lower limbs. Researchers have shown that the partial weight bearing could increase the improvement rate and quality of rehabilitation and decrease the tiredness of subject. The exoskeleton system will increase the stability of human and provide a mean to measure the angle of knee and hip joints. A virtual reality environment is integrated to motivate the subject.

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