Research Status on Ankle Rehabilitation Robot

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REVIEW ARTICLE

Research Status on Ankle Rehabilitation Robot

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Abstract: ***Background***: Ankle is an important bearing joint in the human body. Unreasonable exercise patterns and exercise intensity can cause ankle injuries. This will seriously affect patients' daily life. With the increase in the number of patients, the labor intensity of doctors is increasing. Ankle rehabilitation robot can help doctors free themselves from repetitive tasks, which is, of more practical value.

Objective: To give a general summary of recent ankle rehabilitation robot and introduce the respective characteristics and development including structure type, drive type and rehabilitation training mode.

Methods: This paper investigates various representative studies related to the ankle rehabilitation robot. The structure type, drive type, rehabilitation training mode and applications situation of these ankle rehabilitation robot are discussed.

Results: The characteristics of different types of ankle rehabilitation robots are analyzed. This paper analyzes the main problems in its development. The solutions to the issues and the current and future research on ankle rehabilitation robot are discussed.

Conclusion: The ankle rehabilitation robots are classified into motor drive type, pneumatic artificial muscle and pneumatic cylinder drive type and others. Further improvements are needed in the aspects of mechanical design, safety, virtual reality, brain-computer interface, control strategies and algorithm of bio-syncretic mechanism system of ankle rehabilitation robot. More related patents about ankle rehabilitation robot need to be developed.

Keywords: Ankle rehabilitation robot, ankle rehabilitation training, drive type, linear cylinder drive, motor drive, pneumatic muscle drive type, rehabilitation Principle.

1. INTRODUCTION

Nowadays, people have started to give great importance to their health. We improve our physical fitness by doing all kinds of sports. The ankle is an important part of the human body. Ankle plays an important role in feet standing, walking, running and other activities of human. Most of the body weight is supported by feet, so the ankle is under great pressure. In some cases, unreasonable exercise patterns and exercise intensity can cause ankle injuries. Athletes also are more likely to be injured. Ankle sprain is a common sport injury in daily life [1, 2]. Epidemiological studies abroad pointed out that ankle sprains account for about 30% of all sports injuries [3, 4]. Ankle ligament sprain is the most common sports injury in the joints [5]. The incidence of such injuries is high and the recurrence rate is above 70% [6, 7]. If the treatment of an ankle injury is not timely or incomplete, the ankle ligament will not be able to restore to the original state. This influences joint stability, and sprain reoccurrence along with other sequelae happening more frequently. The normal walking function may also be affected in serious cases [8, 9]. Traditional methods of rehabilitation require physical therapists to provide one-on-one rehabilitation to their patients. The rehabilitation efficacy depends, to a great extent, on the therapist's techniques [10]. With the increase in the number of patients, the labor intensity of doctors increases. Ankle rehabilitation robot can assist doctors and spare themselves from repetitive tasks. At the same time, the rehabilitation device can effectively record the patient's movement data, provide an objective basis for the development of the patient's treatment plan. Thus, doctors can focus on the treatment options and status of the patient. So, the research on ankle rehabilitation robot has become a hot spot.

2. ANKLE STRUCTURE AND REHABILITATION PRINCIPLES

2.1. Anatomy of the Ankle Joint

The ankle is one of the largest weight-bearing joints in the body [11]. The distal tibia and fibula are composed of the

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distal talus and the talus [12], which are shown in Fig. (**1**). The ankle joint connects with the leg and the foot. The ankle includes three joints: the talocrural joint, the subtalar joint, and the inferior tibiofibular joint. The talocrural joint is a synovial hinge joint and it connects the distal ends of the tibia and fibula. The medial margin of the articular fossa consists of the medial malleolus and the distal part of the tibia. The lateral extension of the fibula and tibia constitutes the upper margin. The lateral margin consists of the lateral malleolus and the distal portion of the fibula. The ligaments around the ankle include the medial (triangular ligament) and lateral ligaments. The lateral ligament consists of the anterior talofibular ligament, the calcaneofibular ligament, and the posterior fibular ligament [13]. The tibiofibular ligament includes the anterior inferior tibiofibular ligament, the interosseous and posterior inferior tibiofibular ligaments, and the transverse ligament of the lower leg.

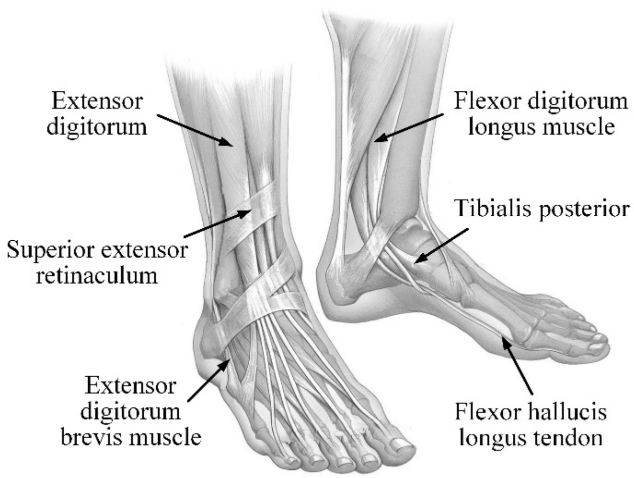

Fig. (1). Muscular and skeletal anatomy of ankle and foot.

2.2. Movement Analysis of the Ankle Joint

The motion of the ankle is actually quite complicated. There are three basic rehabilitation forms for ankle joints: dorsiflexion/plantar flexion, abduction/adduction and inversion/eversion [14]. Ankle physiological data are shown in Table **1**.

(1) Dorsiflexion/plantar flexion: This motion is carried out in the sagittal plane, and it rotates repeatedly around the horizontal axis at a certain speed. When the instep of the foot is lifted upwards, it is dorsiflexion movement, and the reverse is plantar flexion movement. In fact, this movement is the most important movement ofthe ankle joint.

(2) Inversion/eversion: This movement is perpendicular to the other two planes of the frontal section, and rotates repeatedly around the horizontal axis of the sagittal axis at an appropriate speed. When the inside of the foot is lifted upwards and the outside is lowered downwards, the ventral side of the foot turns from the neutral position to the inversion movement. When it is turned upside down, and the opposite direction to the above case is the eversion movement.

(3) Adduction/abduction: This movement is carried out in a cross-section and rotates at a constant rate around a vertical axis. The adduction movement is from the neutral position to the medial rotation, and the abduction movement is from the neutral position to the outside rotation [15].

2.3. Analysis of the Injury of the Ankle Joint

Due to the unique anatomy of the ankle, the ankle is not fit for the plantar flexion movement. So, if the gravity center is unbalanced, it is easy to cause the ankle joint inversion/eversion. It will lead to the internal and external ligament injury, partial avulsion tear or complete rupture, and even fracture [16]. The main clinical manifestations of ankle ligament sprain are:

(1) Ankle lateral collateral ligament injury: Toes will tighten up naturally when the patients' feet touch the ground from the air. The anterolateral surface of the feet will touch the ground first with uneven floor, only to cause lateral ligament injury or sometimes even ligament rupture.

(2) Ankle medial collateral ligament injury: For some reason, if the body's center of gravity is unbalanced, the feet will make the eversion and abduction movement. This may cause medial collateral ligament injury. Clinically, medial collateral ligament injury is very rare.

(3) Lower tibia and fibula ligament injury: When human is affected by the sudden external force, the foot will be fixed, and the calf will be adducted, thus, the lower tibia and fibula are liable to suffer ligament injury. It mainly

Table 1. Ankle Physiological Data.

Motion	Angle Range	Angular Velocity (max)	Torque (N·m)
Dorsiflexion	0°-30°	80°/s	45
Plantar flexion	0°-40°		
Adduction	0°-20°	80°/s	10
Abduction	0°-30°		
Eversion	0°-20°	100°/s	20
Inversion	0°-30°		

occurs in front of the ankle and not outside. And this is mostly broken at the lower end of the tibia and fibula.

2.4. Rehabilitation Principles of the Ankle Joint

After sprain of the ankle, it is necessary to make a timely rehabilitation treatment, otherwise the injured part is prone to swelling and pain, and then it causes recurrent ankle injury. For ruptured ligaments, surgical engagement is required if there are more serious injuries, such as defect rupture, or ligament transplantation [17]. Continuous passive motion (CPM), which is used for rehabilitation of lower extremity surgery or joint after injury, is a new effective method for the joint surgery. [18]. Rehabilitation by exercise can not only increase the nutrition and metabolism ability of articular cartilage, but also prevent sequela of contracture, adhesion and stiffness of articular capsule. At the same time, it does not affect the healing of the incision. Thus, the treatment and functional rehabilitation of the patients are synchronized.

The traditional rehabilitation training for the ankle joint has great limitations. The one-to-one service of rehabilitation technicians and hemiplegic patients leads to a serious shortage of physiotherapists. The rehabilitation training is some kind of repeated and heavy workload. The individual training method is single, but active and passive training cannot be effectively combined. The lack of parametric quantitative evaluation criteria cannot record objective training data.

With the help of a robot, it is possible to solve problems in the traditional rehabilitation training methods for ankle joint. Some advantages of ankle rehabilitation robot are:

(1) Ankle rehabilitation robots do not have a “tiredness” problem, and they can meet requirements of different patients for training intensity.

(2) Ankle rehabilitation robots can liberate people from heavy training tasks. Thus, this will enable therapists to focus on the development of treatment programs, the analysis of training materials, optimization of training contents and improvement of robot functions.

(3) Ankle rehabilitation robot can objectively record the location, direction, speed and force of the affected limb during the training process, and it also provides objective information for therapists to evaluate the therapeutic effect.

(4) The use of ankle rehabilitation robot makes remote and centralized treatment possible [19].

3. STATE OF THE ART OF ANKLE REHABILITATION ROBOT

According to the drive type, ankle rehabilitation robot can be classified into: motor drive type, pneumatic muscle drive type, linear cylinder drive and other new drive types.

3.1. Motor Drive Type Ankle Rehabilitation Robot

Zhao *et al.* from Shenzhen Institutes Advanced Technology of Chinese Academy of Sciences developed an ankle rehabilitation device, which is shown in Fig. (**2**). It includes the moving platform, fixed platform and adjusting mechanism [20, 21]. The moving platform connects with the fixed platform by the adjusting mechanism. The top of the moving platform is provided with a foot pedal, and the first ball joint is located at the bottom of the moving platform. The adjusting mechanism comprises the driving device, three supporting rods and a central constraining rod. The lower end of the central constraining rod connects with the fixed platform, and the upper end connects with the first ball joint. The driving device, the first connecting rod and the second connecting rod are sequentially connected to realize the horizontal rotation movement, and a second ball joint arranged at each connecting point drives the movable platform to rotate. The foot pedal is equipped with a pressure sensor and a functional electrical stimulation electrode. This device adopts two driving devices to realize the three degrees of freedom rotation of the rehabilitation device, so that the rehabilitation device is easy to control. The structure is simplified and the cost is reduced. The ankle rehabilitation device provides three kinds of control: passive control mode, active control mode and impedance control mode. According to the patients’ condition, patients can choose the appropriate control mode for training, so as to achieve a good effect on rehabilitation.

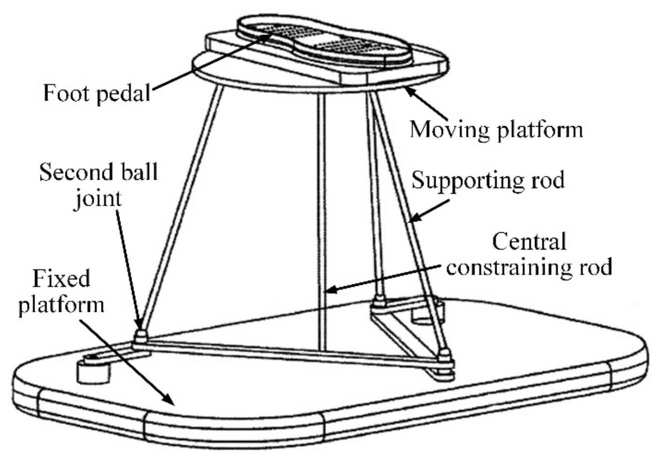

Fig. (2). An ankle rehabilitation device developed by the Shenzhen Institutes Advanced Technology CN104068991.

Li *et al.* from Beijing University of Technology developed an ankle rehabilitation device, which is shown in Fig. (**3**). This device includes base, the active limb chain, the constrained branch and moving platform [22, 23]. The active branches include the left active limb chain and the right active limb chain, and the left and right limb chains are UPS limb chain, and symmetrically distributed on the lower platform. The constrained branch chain comprises a lower rotary link, a left link, a right link and an upper arc link. The lower rotary link is arranged on the rotary shaft through a connection sleeve. The movable platform includes an adjusting block, an upper platform and a lower platform. By adjusting the stopper and the upper and lower adjusting devices, the relative position of the human foot and the upper platform can be adjusted. The moving platform of this device can rotate in three directions, so the rotation center the device and the ankle are coincident. It has the advantages of simple structure, convenient use, small occupation volume and low manufacturing cost.

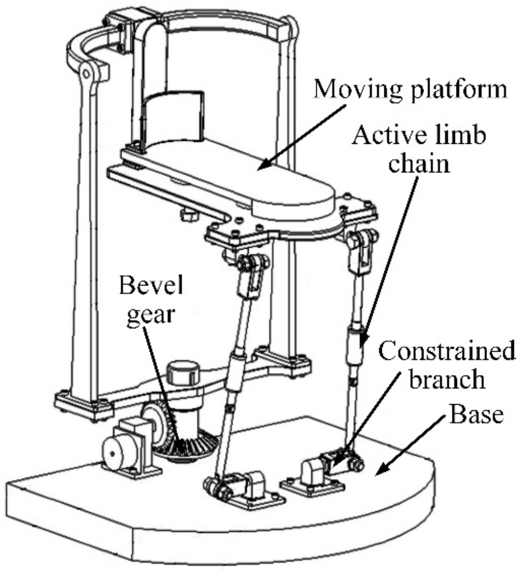

Fig. (3). An ankle rehabilitation device CN105125380.

Li *et al.* also invented a parallel active/passive ankle rehabilitation training device. It mainly consists of the bottom plate, the fixed platform, the moving platform and three evenly distributed limb chains. Each limb chain includes a motor bracket, a drive motor, a jaw clutch, a fixed platform rotary pair, a dual elastic rotary pair, a moving platform rotary pair, the moving platform connecting rod and the fixed platform connecting rod [24-26]. This device is shown in Fig. (**4**). The movable platform can realize three Degrees Of Freedom (DOF) rotation movement, and the rotation center of the device and the ankle are coincident. During the rehabilitation training of ankle joint, it can help the human ankle achieve three movements: dorsiflexion/plantar flexion, abduction/adduction and inversion/eversion. Through the clutch and the dual elastic rotation pair, the active, passive or semi-active rehabilitation modes of the ankle can be realized. It can help patients with ankle training accurately, and meet the needs of patients with varying degrees.

Li *et al.* also developed a 3-DOF 3-UPS/RRR parallel mechanism for ankle rehabilitation It adopts three active branches [27]. In order to avoid the singularity of the mechanism, the three active branches are tilted, which is shown in Fig. (**5**). Meanwhile, the design of the constraint branch and moving platform makes the rotation center of the mechanism coincide with the patients' ankle rotation center. As the ankle rehabilitation exercise requires limited space, three active branches have the same tilt angle to avoid the singularity.

Zhang *et al.* from Nantong Meijia Robot Technology Co., Ltd. invented a parallel ankle rehabilitation robot [28]. This robot includes the base, the lower link, the upper link, the adjusting pad, adjusting hole, the motor, the absolute

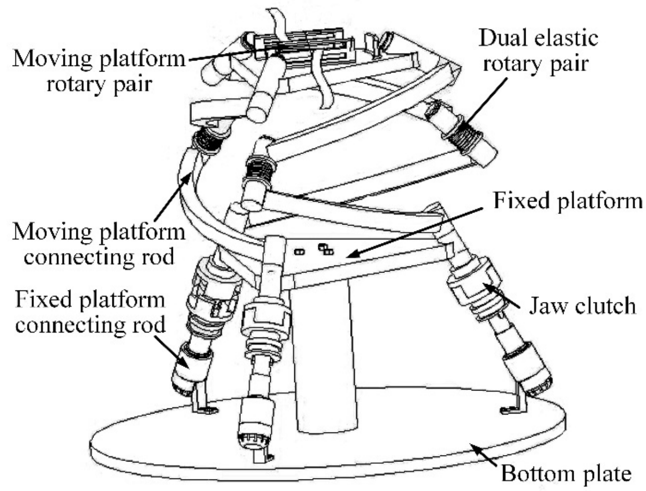

Fig. (4). A parallel active/passive ankle rehabilitation training device CN103070757.

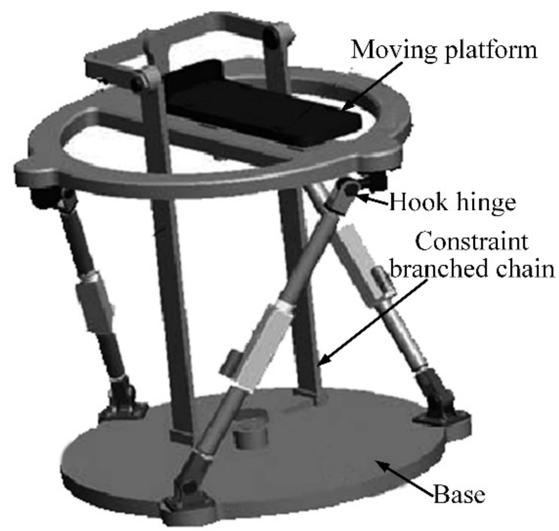

Fig. (5). The model of 3-UPS/RRR parallel mechanism for ankle rehabilitation.

encoder, the laser and the moving platform. It is shown in Fig. (**6**). The moving platform connects with the base through three identical branches. The structure of each branch is as follows: the shell of the motor locates at the base, and the extending shaft of the motor is fixedly connected with the lower connecting rod. The connection of the lower and upper connecting rod, the upper connecting rod and the moving platform are rotary pair. The motor shaft extends out, and the axis of the rotary pair Ⅰ and the rotary pair Ⅱ intersect at a central point. At the same time, the three central points of the three branches must intersect at one point. With the help of this robot, the foot of the patient can be placed safely and reliably in the correct position. The rotation center of the rehabilitation device and the ankle are coincident. This ankle rehabilitation robot has the advantages of compact structure, good interchangeability, safety and reliability.

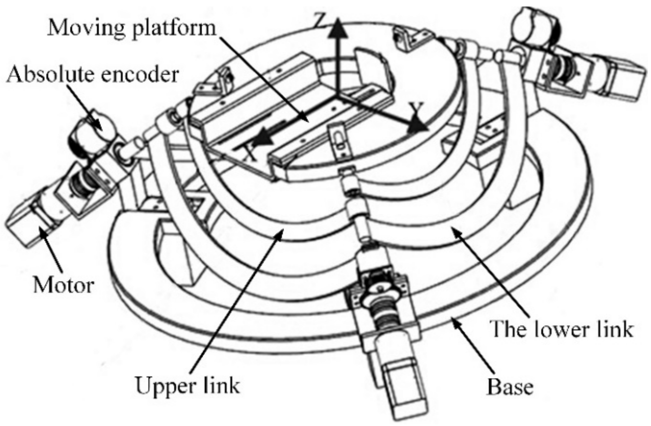

Fig. (6). A parallel ankle rehabilitation robot CN104887452.

The existing transmission mechanism has the disadvantages of poor transmission, easily causing secondary injury to the patient, complicated structure, high production and maintenance costs. In order to solve these problems, Cao *et al.* from Jiangnan University invented a transmission mechanism for ankle rehabilitation robot, which is shown in Fig. (**7**). It includes 2R1T parallel mechanism and two-dimensional moving mechanism [29]. The 2R1T parallel mechanism includes a moving platform and an intermediate transition platform. Both ends of the moving platform and the intermediate transition platform in the X-axis and the Y-axis direction are connected by a pair of symmetrically arranged first and second branches, respectively. So, the moving platform is driven to rotate along the X-axis and the Y-axis and move along the Z-axis. The rotation center of the patients' ankle joint coincides with the 2R1T parallel mechanism. The accompanying movement is eliminated fundamentally, and the secondary damage to patients can be prevented. The two-dimensional moving mechanism includes a third branch. In order to realize the movement of the intermediate transition platform and the moving platform along the X-axis and the Y-axis, the third branch connected with the intermediate transition platform. At the same time, the overall structure of the transmission mechanism is simple with good stability. It is easy to manufacture, assembly and maintenance.

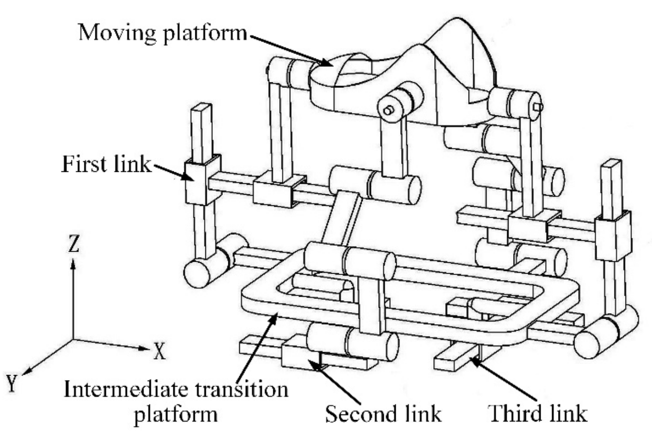

Fig. (7). A transmission mechanism for ankle rehabilitation robot CN106983632.

Wang *et al.* from Beijing Jiaotong University developed an ankle rehabilitation device, which includes a base, a moving platform, an active branch and a constrained branch [30-33]. The base comprises a pedestal and a supporting platform, and the supporting platform is fixed on the pedestal by the supporting rod. This ankle rehabilitation device is shown in Fig. (**8**). The constraint chain includes a load-bearing platform, a left supporting connecting rod, a right supporting connecting rod and an arc connecting rod. The constraint chain is arranged on the base. The load-bearing platform is located on the support rod. Active branches include the first, the second and the third active branch, which are juxtaposed RUS branches. The design of constrained branch chain and the moving platform achieves three DOF rotation movements. This not only ensures the coincidence of rotation centers, but also constrains the orthogonality of the branched chain axes.

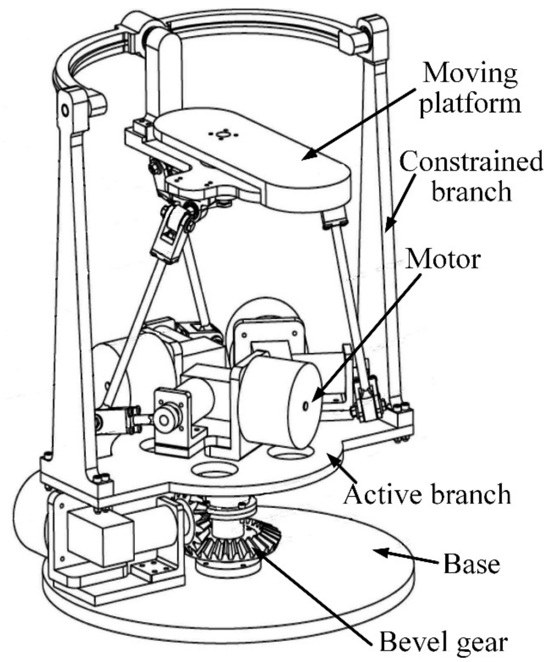

Fig. (8). An ankle rehabilitation device CN103479502.

Wang *et al.* from Chongqing University of Posts and Telecommunications also invented a parallel ankle rehabilitation device [34, 35], which is shown in Fig. (**9**). The driving part of this patent eliminates the bevel gear structure. This device can realize three movements: dorsiflexion/plantar flexion, abduction/adduction and inversion/eversion. According to different sizes of different patients' foot, the distance from the platform to the rotating center can be adjusted. Thus, the rotation center of the patients' ankle joint coincides with the parallel ankle rehabilitation device. The redundant drive arrangement scheme of 4 RUS branch chains is adopted to ensure good movement performance.

Wei *et al.* from ShaoGuan Spark Technology Co., Ltd. developed a novel ankle rehabilitation robot and studied its control method. This robot consists of the electric cabinet, the base, the drive motor, encoder, 3-RRR spherical parallel mechanism and foot pedal. The 3-RRR spherical parallel mechanism is located between the bottom base and the upper foot pedal, and it has three identical moving branches. Each moving branch consists of three revolute pairs and two connecting rods [36, 37]. The robot has three rotational degrees of freedom, and the workspace satisfies the motion range of ankle. And it also meets the requirement of the high flexibility and bearing capacity of the ankle. It is shown in Fig. (**10**). According to different stages of ankle rehabilitation of post-operative, two rehabilitation training modes are designed: exercise function training mode and muscle strength training mode. The control system of robot is established by position control mode under the exercise function training. In the muscle strength training mode, the impedance control mode is adopted. The “mass-damping-spring” force model is used to ensure that the robot can interact with people flexibly and safely under the passive work.

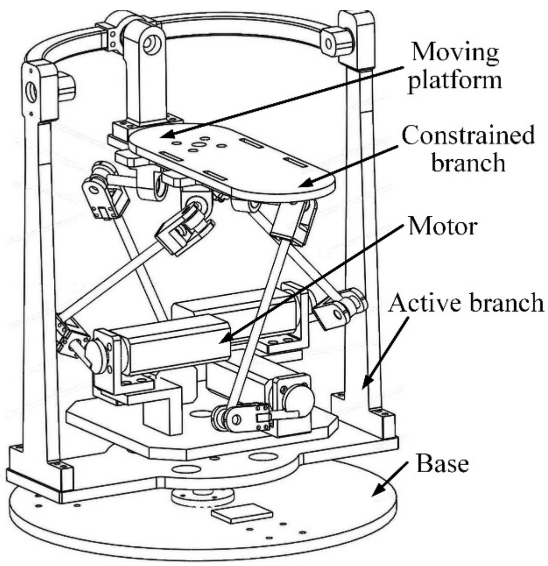

Fig. (9). A parallel ankle rehabilitation device CN106974805.

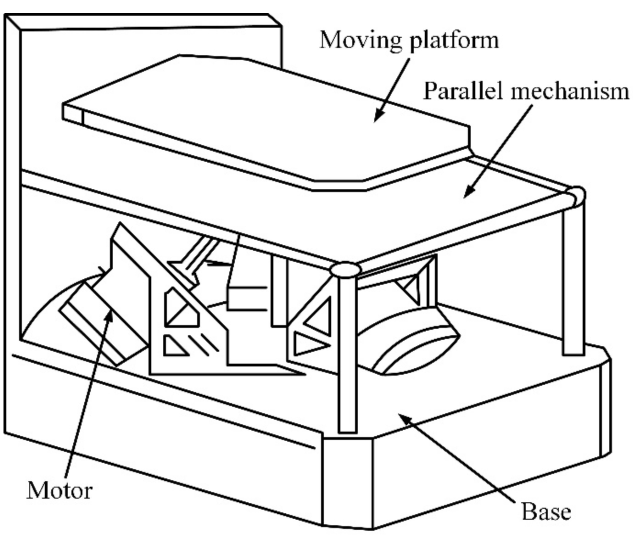

Fig. (10). A novel ankle rehabilitation robot CN107050763.

Yao *et al*. from Fuzhou University invented a novel adjustable ankle rehabilitation device including base, three sub-branch mechanisms, the fixed platform and moving platform [38-40]. It is shown in Fig. (**11**). Each branch includes two linear actuators, a rocker and a connecting rod. The fixed and moving platforms are fixed by the central branch. The central branch supports the moving platform by the spherical pair, and the three adjustable linear drives are evenly distributed in the base. The ends of the push rod of the three linear actuators are respectively connected with the outer ends of three rockers. The inner ends of the three rockers are respectively hinged with the fixed platform and the outer ends of the three rockers are respectively hinged with the moving platform through three connecting rods. The linear actuator can realize the reciprocal motion, and then it pushes the rocker to realize the swing movement. The rocker is connected with the connecting rod. Then the connecting rod drives the end slider. The three branches drive the moving platform which can rotate around the support bar. Therefore, the ankle rehabilitation movement can be simulated effectively. The reconfigurable mechanism includes three linear actuators and a base. It locates at the lower part of the robot, which is shown in Fig. (**12**). The adjustable ankle rehabilitation device is simple, easy to control and low cost. It is easy to adjust the ankle rehabilitation range. It has the characteristics of quick response to input and output. It can satisfy the need for ankle rehabilitation treatment or lower limb muscle relaxation of different patients. The device can fix the foot directly on the platform, and the function of treatment and relaxation can be realized through the action of a linear driver. It can be widely applied to clinical treatment and relaxation of ankle and leg muscles.

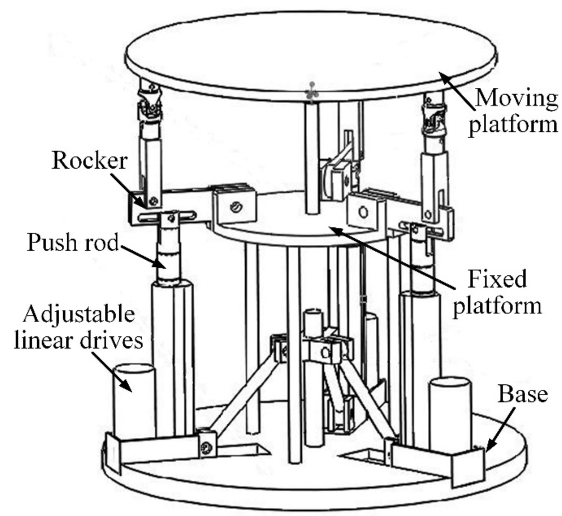

Fig. (11). An ankle rehabilitation device CN103156756.

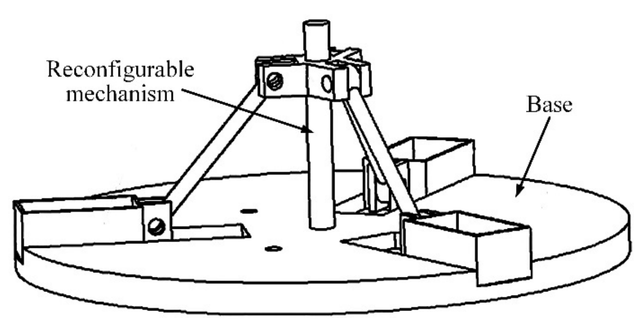

Fig. (12). Reconfigurable mechanism.

Malosio *et al*. developed PKAnkle. This ankle-foot rehabilitation robot is designed according to Gosselin's robot Agile Eye, which is shown in Fig. (**13**). The kinematics of the Agile Eye structure is limited to the link alignment [41, 42]. A key feature of this rehabilitation robot is the ability to choose the appropriate training program/model for patient based on specific circumstances. PKAnkle allows patients to perform comfortable physical exercises. The prototype is shown in Fig. (**14**).

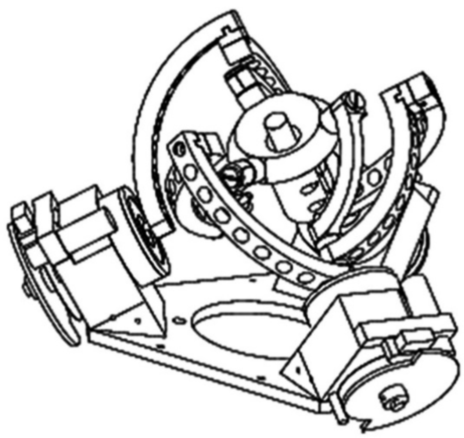

Fig. (13). Gosselin's Agile Eye.

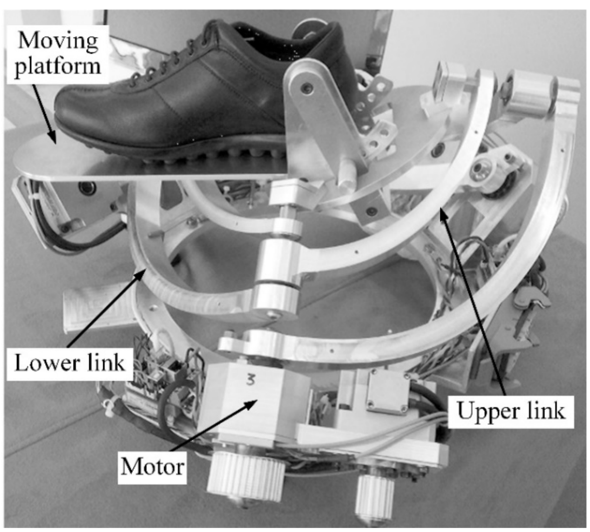

Fig. (14). PK Ankle prototype.

Enferadi *et al.* developed a novel spherical parallel ankle rehabilitation robot. And the moving platform only can realize the rotational movement. It is shown in Fig. (**15**). The robot can completely rotate around an axis. The 3(RSS)-S fully spherical robot is mainly composed of a fixed platform, a moving platform and a non-moving spherical joint which is composed of a fixed fixed spherical joint and three similar legs [43, 44]. Each leg is composed of three joints which are called Revolute (R), Spherical (S) and Spherical (S). These joints are actuated with a motor. This manipulator can be defined as a spherical parallel manipulator. The rigid body can be moved into any direction. The rigid body can rotate around the vertical axis if the motors work simultaneously. It is an advantage of this manipulator.

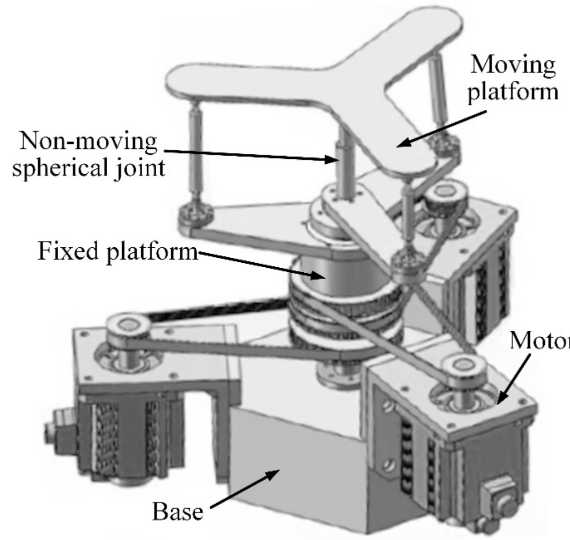

Fig. (15). A novel spherical robot with unlimited rotation around an axis.

Ayas and Altas developed a redundantly actuated ankle rehabilitation robot, which is shown in Fig. (**16**). It has two exercise modes which are passive and active Range Of Motion (ROM) exercises. The proposed rehabilitation robot is mainly composed of a motionless base platform and a moving platform. They are connected through 3 extensible legs and 1 strut which are located at the center [45, 46]. The extensible legs are used to rotate the upper platform. They are composed of DC electrical actuators. The universal joint is installed at the bottom end of the leg and the spherical joint is installed at the upper end. They support the upper platform and limit the mobility of the device to 2 DOFs by fastening both moving and base platforms. This structure has high stiffness capability and singularity free workspace.

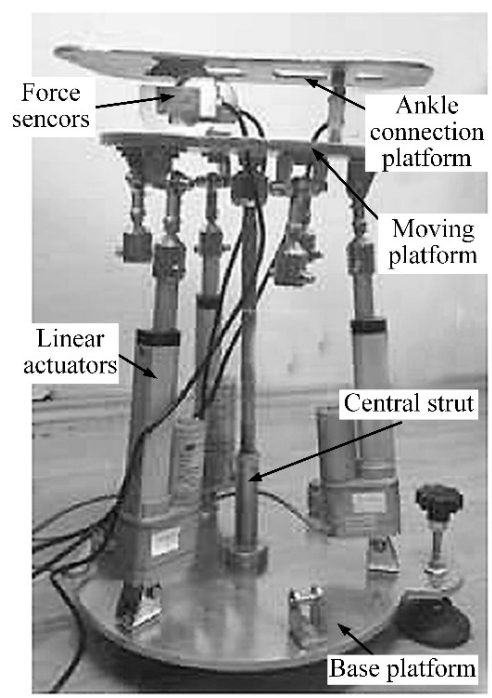

Fig. (16). A redundantly actuated ankle rehabilitation robot.

Rosado *et al.* designed a passive ankle rehabilitation prototype based on a structure of parallel robot with a mechanism of the type of 2-RRSP (two closed kinematic chains and consisting of joints: revolute-revolute-sphere in slot fixed post with sphere) [47]. Free software is used to develop computer programs associated with rehabilitation exercises. In the prototypical construction, most parts use aluminum and bars that connect the actuator arm to the upper platform use steel. Steel is also used for the guide posts and the connecting bases to be superior to the fixed columns of the platform. The sketch of this robot is shown in Fig. (**17**). A photograph of this is shown in Fig. (**18**). This mechanism is driven by a geared motor. It provides enough torque and suitable speed.

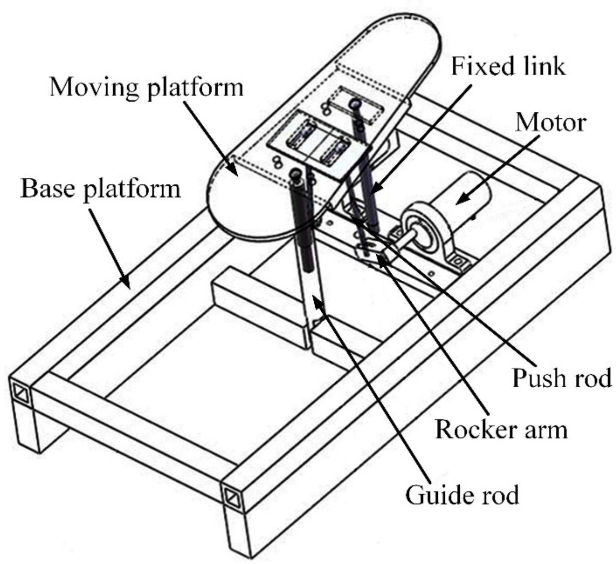

Fig. (17). Sketch of a passive ankle rehabilitation robot.

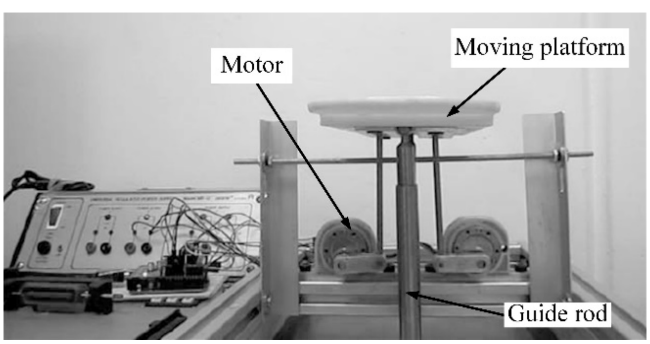

Fig. (18). Prototype of a passive ankle rehabilitation robot.

Li *et al*. developed a Parallel Manipulator (PM) with redundant actuation, which is shown in Fig. (**19**). The parallel manipulator consists of a fixed base, a moving platform, and 4 DOF actuated limbs [48, 49]. The redundantly actuated parallel manipulator is composed of four limbs and it has three DOFs. The manipulator can be defined as a 2UPR-2PRU parallel mechanism (where P defined as an actuated prismatic joint, R defined a revolute joint, and U defined a universal joint). It is actuated by four prismatic joints. Two joints are installed on the base. This structure can reduce the dynamic quality and improve dynamic response. This mechanism has only 16 single-DOF joints which actuated using four prismatic joints. It can be found for the proposed PM which has one translational DOF and two rotational DOFs through the mobility analysis.

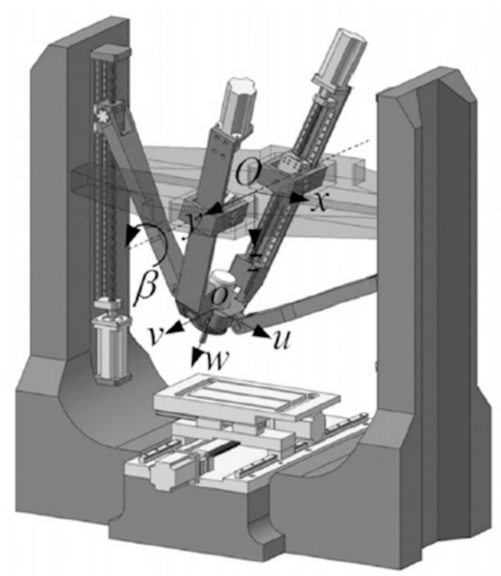

Fig. (19). A parallel manipulator with redundant actuation.

Du *et al*. developed a novel ankle rehabilitation 3-RRS spherical parallel mechanism, which is shown in Fig. (**20**). It is composed of eight parts which are the base, the moving platform, support, motor, crank, coupler, foot support, and expansion device. The rotations of the moving platform around the center of the sphere are driven by three motors through the cranks. A 3-revolute–revolute–spherical joint's SPM of this robot generates rotation analogy to human ankles [50]. This robot cannot only be used in clinical treatment but also can be used at home, hotels, and fitness centers for ankle muscle relaxation.

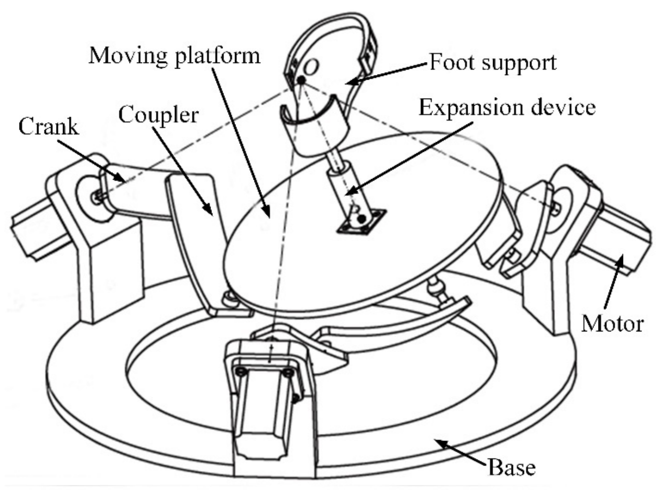

Fig. (20). The 3-RRS SPM for ankle rehabilitation.

Zeng *et al*. developed a decoupled parallel ankle rehabilitation robot, which is shown in Fig. (**21**). The mechanism consists of a moving platform, static platform and three branches of connecting two platforms [51]. Compared with other ankle rehabilitation mechanism, the kinematic pair of this mechanism is more complex. The kinematic chain is slightly longer, but all kinematic pairs are lower pairs, easy to machining. The realization of decoupling makes the control simple, and conducive to ensuring the safety and reliability of rehabilitation. The decoupling mechanism eliminates the coupling among different branches, simplifies the control and optimizes the size of the decoupling mechanism by optimizing the output parameters. This robot has no singular point in the workspace.

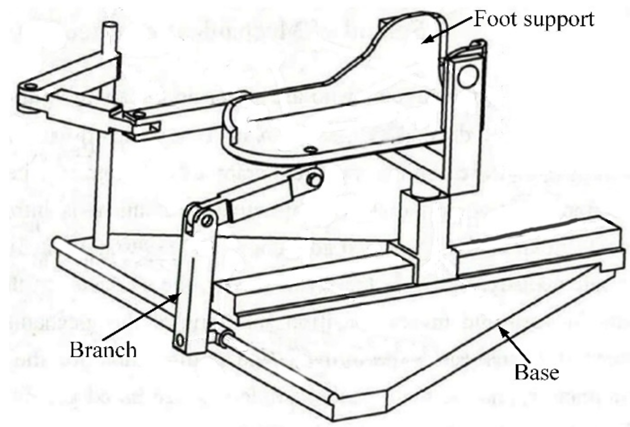

Fig. (21). A decoupled parallel ankle rehabilitation robot.

Sun *et al*. developed a parallel machine ankle rehabilitation robot, which is shown in Fig. (**22**). The mechanism has five DOFs, and it drives by five motors to realize the smooth and reliable movement [52]. Each motor of the link is installed on the lower legs. The distance between two joints is controlled by Motor 1 to 4. This is realized by changing the angle between the upper leg and the lower leg. The rotation angle of the universal joint in one direction is controlled by Motor 5. The rotation of the platform around the frontal axis is driven mainly by Motor 2 and Motor 4. In this process, Motor 1, Motor 3, and Motor 5 are mainly used to keep the platform in a stable state to move smoothly and stably. Similarly, the rotation of the platform around the sagittal axis is driven by Motor 1 and Motor 3. The Motor 2, Motor 4 and Motor 5 are used to keep the platform to move smoothly and stably.

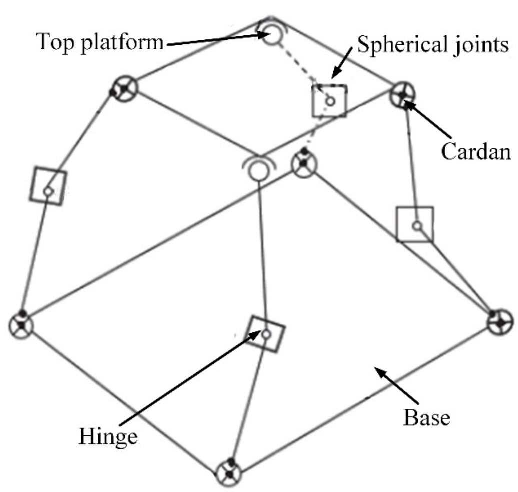

Fig. (22). Ankle robot mechanism.

Wei *et al*. developed an ankle rehabilitation which is composed of a parallel mechanism with six degrees of freedom, which is shown in Fig. (**23**). The mechanism is mainly composed of the platform, three links and base [53]. Motors drive the links, one motor is designed for middle transmission mechanism, and the other motors are designed for base transmission mechanism. The three links have the same basic configurations, but the size of link 2 and 3 and link 1 is different. The interference of the universal joint could occur at a designed angle range. To realize the process of movement within the normal operating range, the angle between the upper link and the universal joint connecting position should be changeable. The base transmission mechanism is composed of two bevel gears, cross block, reducer. Reducer is connected to the transmission mechanism. The cross block is driven by it through a bevel gear pair. The position of the lower connecting shaft is controlled by the cross block. Considering the speed of the various parts to be low, the sleeve is designed to connect fixed parts and moving parts. This design can save space and simplify the mechanism.

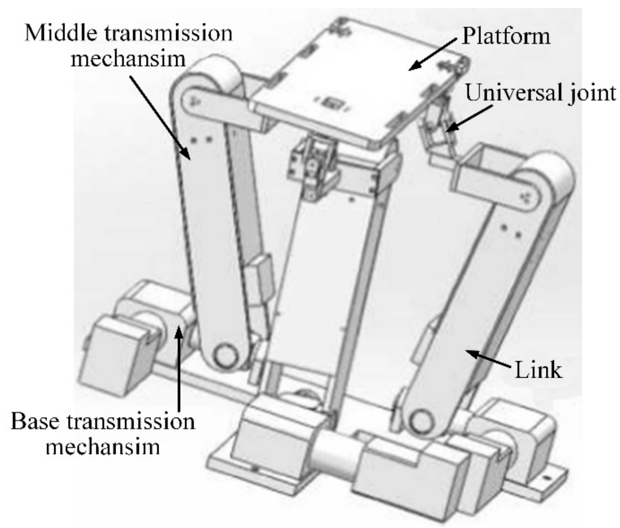

Fig. (23). Ankle robot mechanism.

Nurahmi *et al*. developed a 3-RPS manipulator for ankle rehabilitation, which is shown in Fig. (**24**). The leg is connected with the base, and its shape is an isosceles triangle. The platform is designed into the shape of an isosceles triangle which is used to place on the foot [54]. The 3-RPS manipulator can realize four rehabilitation movements which are dorsiflexion, plantar flexion, supination and pronation. To perform dorsiflexion of the ankle joint, the moving platform can realize the movement of tilting up to 90°. The manipulator is not a singular configuration when the ankle joint is at rest position. Thus, when the ankle joint is at rest position and the foot is at 20° below the transverse plane.

Han *et al*. developed a parallel robot mechanism for ankle rehabilitation, which is shown in Fig. (**25**). The parallel mechanism consists of 3 RUPS branched chain, 1 constraint axis, moving platform and static platform [55]. The upper platform is a moving platform, and the lower platform is a static platform. The 3 same branches consist of bearings (revolving pair R), Hooke hinges U, electric pushing rods (prismatic pair P), spherical hinge S. Its lower ends are connected with the static platform by bearings, so that the RUPS branched chain can only revolve around the static platform. The constraint axis is constrained by ball joints, thus 3 moving degrees of freedom of the moving platform are restricted, so the moving platform can rotate around the three axes. This robot mechanism has high rigidity with large bearing capacity.

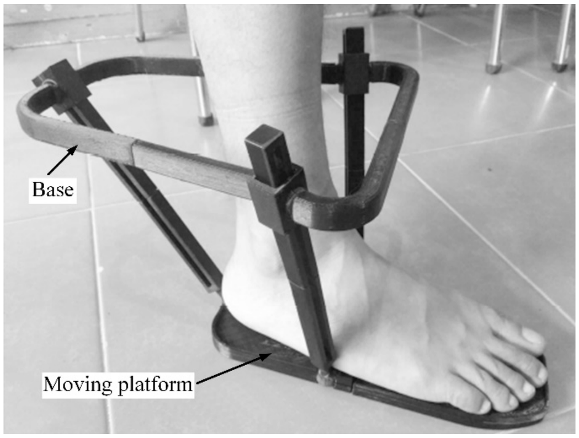

Fig. (24). An ankle rehabilitation device.

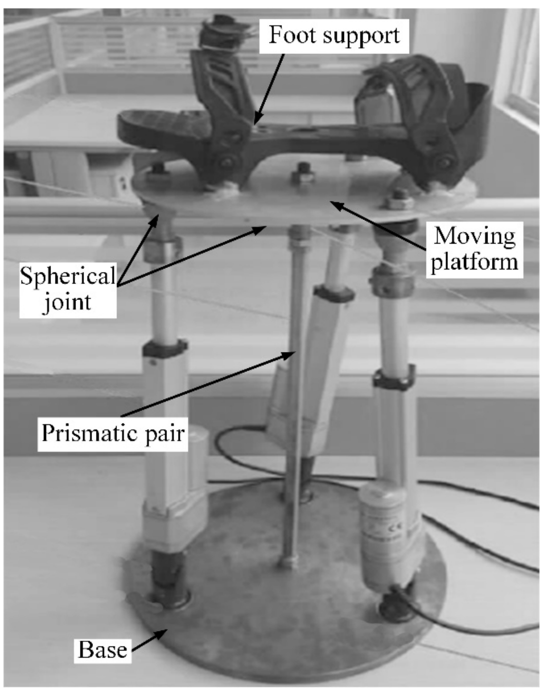

Fig. (25). 3-RUPS/S ankle rehabilitation robot.

Li *et al*. developed a novel ankle rehabilitation robot, which is shown in Fig. (**26**). This robot is composed of a base platform, a rotating platform (rotate around a vertical shaft), two bearing rods, three linear actuators, a rocker, a connecting rod, a moving platform and a motor [56]. The rotating platform is driven by the motor. The movement of ankle rehabilitation can be simulated.

3.2. Pneumatic Muscle Drive Type Ankle Rehabilitation Robot

Zhang and Xie *et al*. invented the parallel ankle rehabilitation robot, which is shown in Figs. (**27** and **28**). This robot includes a base, a support frame, adjusting mechanism and movement mechanism [57-64]. The support frame is inserted on the base. An adjustable mechanism is installed on the support frame. The adjustable mechanism comprises a main rod, a forearm rod and a leg support rod. The front end of the main rod connects with the forearm rod, the leg support rod connects with the main rod, the forearm rod connects with the connecting rod, and the main rod and the supporting frame are connected movably. Pneumatic muscle or linear motors are used as actuators. The front end of the driving mechanism connects with the connecting rod of the adjusting mechanism. The end of the driving mechanism connects with the movement mechanism and the movement mechanism is clamped with the end of the main rod. This robot can adjust the range of motion to adapt to different patients, realizing the three degrees of freedom ankle exercise training. The pneumatic muscle is used as the actuator, so it has advantages of good flexibility and strong adaptability.

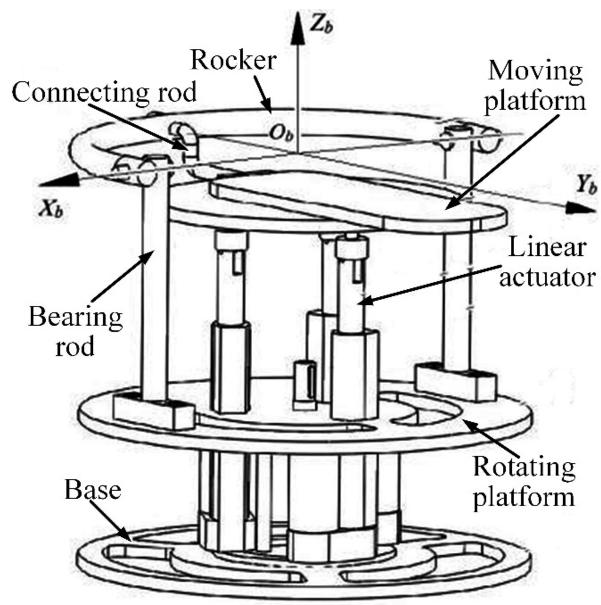

Fig. (26). An ankle rehabilitation robot.

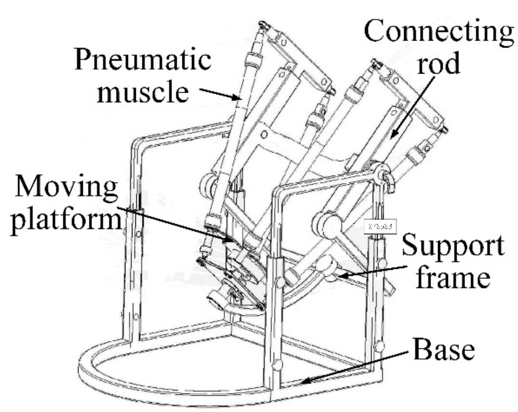

Fig. (27). A parallel ankle rehabilitation robot CN105105970.

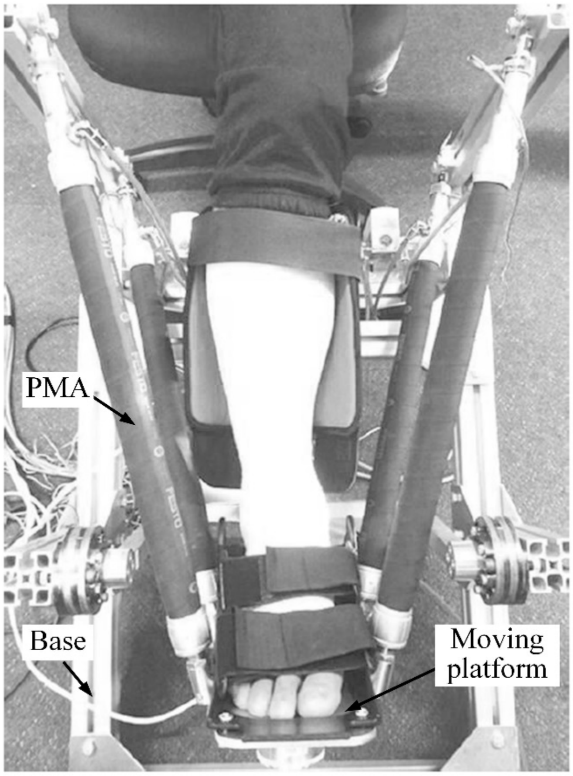

Fig. (28). A compliant ankle rehabilitation robot.

Liu *et al*. from Tianjin University developed three degrees of freedom ankle rehabilitation device driven by pneumatic muscles, which is shown in Fig. (**29**). This device includes the bottom fixed platform, a second drive mechanism, a middle elastic support mechanism, the moving platform, the upper movable frame, the middle frame and the first drive mechanism [65]. The middle frame is arranged between the bottom fixed platform and the moving platform, and the upper moving frame is hinged on the bottom surface of the moving platform. The bottom of the middle frame is fixed on the middle of the bottom fixed platform through the middle frame base, and the middle of the middle frame is provided with a middle elastic support mechanism. The bottom of the middle elastic supporting mechanism is fixed on the middle frame base of the middle frame. The top of the middle elastic supporting mechanism extends out of the upper end of the middle frame, and it connects with the upper moving frame. The upper moving frame is hinged on the bottom surface of the moving platform. Under the premise of ensuring the device as simple and compact as possible, this device realizes three degrees of freedom in two directions of rotation and one direction of movement. It can also realize more degrees of freedom of complicated movements of the ankle joint. The rigid actuator of the traditional robot is replaced by a flexible pneumatic muscle. With advantages of high rigidity, high response and no cumulative error of the parallel mechanism, it also has good flexibility, safety and pollution-free. Based on that, it is very suitable for working under the environment of human-computer interaction.

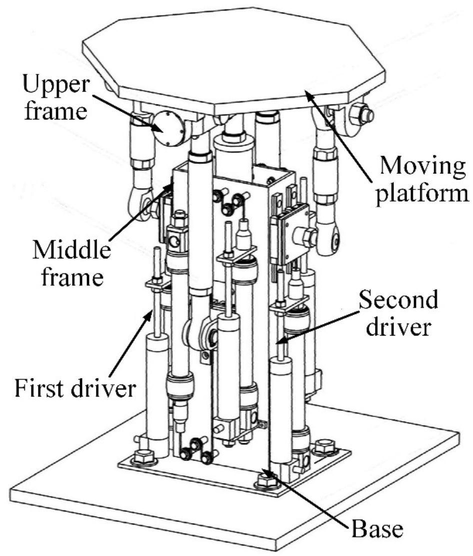

Fig. (29). A three degree of freedom ankle rehabilitation device driven by pneumatic muscle CN105943306.

Jamwal *et al.* from the University of Auckland developed a pneumatic muscle driven wearable parallel robot for ankle joint rehabilitation, which is shown in Fig. (**30**). It is mainly composed of two platforms which are fixed Platform (FP) and Moving Platform (MP). Two aspects of the design of the ankle joint are considered. Firstly, the ankle stays still while the platform is moving. Secondly, the actuators are placed under the platform in order to have a relatively large shift of the tibia. Because PMA has the advantage of the light weight, low cost and high-power weight ratio, it is used by the mechanism. The mechanism is driven by pneumatic muscle actuator [66-77]. The inherent flexibility of PMA (Pneumatic Muscle Actuator) requires redundant drivers, so 4 PMA are required to implement the 3-DOF ankle movement. In addition, in order to design the compact wearable robot to achieve the required motion range, the extension cable is connected with PMA to manipulate the mobile platform of the parallel robot. The ability of a parallel robot is suitable for a relatively small but with very high stiffness of the ankle movement.

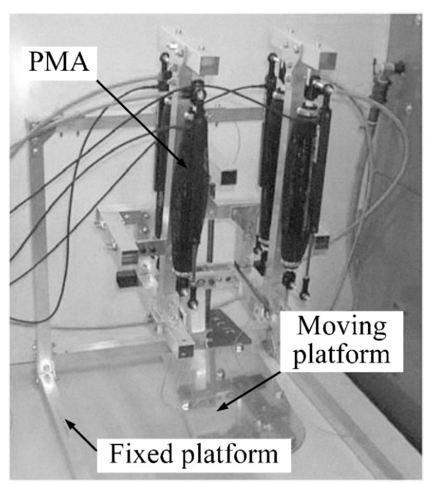

Fig. (30). A wearable parallel ankle joint rehabilitation robot driven by pneumatic muscle.

Cao *et al*. developed a parallel ankle joint rehabilitation robot, which is shown in Fig. (**31**). This robot is mainly composed of four pneumatic muscles, fixed platform, moving platform, X axis joint, Y axis joint, Z axis joint, U type transverse frame of Y axis joint and arc frame of X axis joint [78]. The moving platform includes the U type transverse frame of Y axis joint, the X axis joint arc type longitudinal frame and Z axis joint. This robot can realize the moving platform (ankle) around the rotary motion of the Y axis (dorsiflexion/plantar flexion movement) around the X axis (inversion/eversion movement) and around Z axis rotation (abduction/adduction movement). The drive part is four pneumatic muscles, and the driving characteristics of the pneumatic muscle are only applied the axial tension. It cannot generate the axial thrust. The contraction and recovery of pneumatic muscle can be achieved by the inflating and deflation for pneumatic muscle. While the inflating and deflation of the four PMAs are performed simultaneously, the moving platform can realize the rotation movement around three orthogonal axes of the X-axis, Y-axis, Z-axis, and three axes intersect at one point, which is the ankle center. In the initial position of the moving platform, the U type transverse frame of Y-axis joint being a 45° angle with the horizontal plane. The X-axis joint arc type longitudinal frame is located at the vertical plane, and the moving platform is parallel to the plane of the fixed platform.

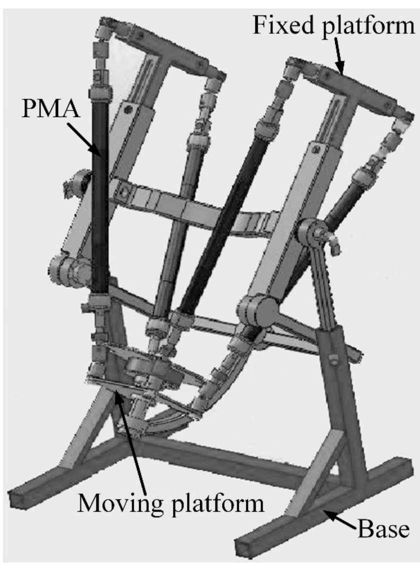

Fig. (31). A parallel ankle joint rehabilitation robot developed by Huazhong University of Science and Technology.

3.3. Linear Cylinder Drive Type Ankle Rehabilitation Robot

Yonezawa *et al*. from Tokyo University of Science developed a kind of ankle rehabilitation device called PHARAD-, which is shown in Fig. (**32**). Two functions are designed in this device which is motion measurement and passive exercise of human foot. During the rehabilitation of the passive exercise, the foot pedal of the patient's foot is driven by the power source. The parallel link mechanism which can be called the Stewart platform is designed to measure and control the posture of the foot plate. Two functions including the motion measurement and the passive motion are realized by this device [79]. Six pneumatic cylinders are used in the actuators of this device. Displacement sensors are installed on them. The cylinder rods can move in the target value because the Proportional Integral Derivative (PID) controller is used to control the compressed air. According to the length of each cylinder, the position of the pedal and the angle of rotation can be calculated. The mechanism is characterized by the ability to meet the complex ankle movement, to measure data in motion, and to feed back in real time.

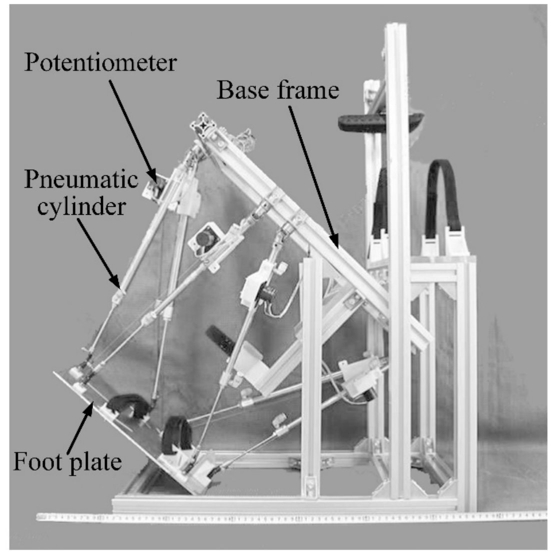

Fig. (32). PHARAD by Tokyo University of Science.

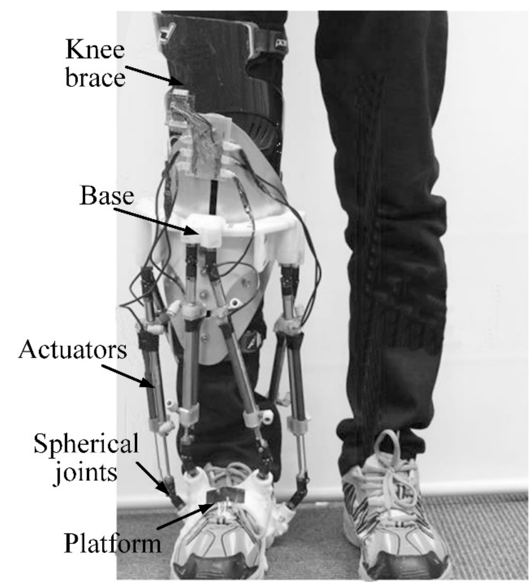

Fig. (33). Stewart platform type ankle-foot device.

Nomura *et al*. also developed an ankle-foot device for trip prevention support using a Stewart platform, which is shown in Fig. (**33**). By using six pneumatic cylinders synchronously, the input motions of the ankle joint in six degrees of freedom can be reproduced by this device. This device can be divided into two parts which are the base and the platform. They are connected through 6 direct-motion actuators and 12 spherical joints [80, 81]. The direct-motion driving function is realized by a pneumatic linear cylinder and a potentiometer installed in parallel. Comparing with the serial actuators, its operating range is small. But this doesn't affect the support function of this device because the ROM of the ankle joint is also small.

Rastegarpanah1 *et al*. developed a parallel robot with 6 degrees of freedom to rehab the stroke patients, which is shown in Fig. (**34**). The top and base of this device are connected through six servo linear actuators by using six rolling spherical joints and six universal joints. A footwear with adjustable straps is installed on the top platform which is made by lightweight polycarbonate [82, 83]. This device can evaluate the process of the recovery, and more in-depth repetitive movements will be generated on the patient. A Graphical User Interface (GUI) can assist the physiotherapist to choose the proper exercise for the patient from a dedicated database. It can also monitor the progress of recovery of patients, and conveniently select suitable exercises for each patient. The robot can realize all of these foot trajectories of different rehabilitation exercises successfully.

Rastegarpanah1 *et al*. proposed an ankle rehabilitation with a 9-DOF hybrid parallel robot. It includes two movable platforms and a stationary platform. They are connected through the serially connecting of nine linear actuators [84]. The parallel hybrid robot can simulate the movement of an ankle in a gait cycle which includes the movement in all three body planes, plantarflexion/dorsiflexion, abduction/adduction, and inversion/eversion.

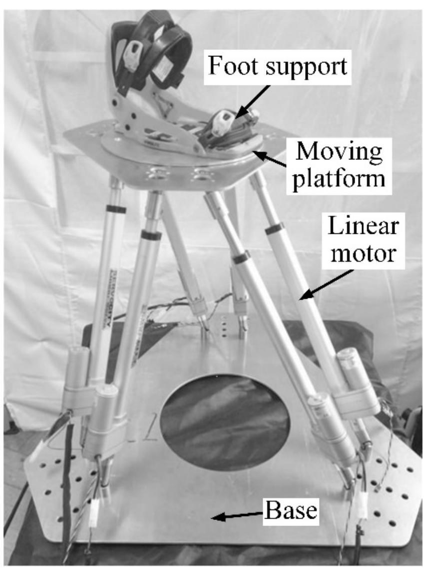

Fig. (34). 6 DOF parallel robot Prototype for ankle rehabilitation designed by the University of Birmingham.

Vallés *et al*. developed a 3-PRS parallel manipulator for ankle rehabilitation, which is shown in Figs. (**35** and **36**). This parallel ankle rehabilitation robot is developed by the Universitat Politècnica de Valencia which has the advantage of low-cost. This robot can realize the passive, active-assistive and active-resistive exercises. It is composed of three kinematic chains. The configuration of each chain is PRS [85, 86]. The prototype has three DOFs. The two DOFs of the prototype are used to realize the angular rotation in two axes (Dorsi/Plantar Flexion and Eversion/Inversion) and the other DOF is used to realize the translation motion (height). The physical system is composed of a moving platform and a base. They are connected with each other through three legs. A direct drive ball screw (prismatic joints) drives each leg. The ball screw is connected with the coupler bar through the revolute joint. A spherical joint is connected with the moving platform through the connection of the upper part of the coupler. The lower part of the ball screws is perpendicularly attached to the platform's base. Ball screws are installed on the base in an equilateral triangular configuration. The rotational movement of the motor can be transformed into linear motion through the ball screw. The brushless DC servomotors are installed on each leg. An orthopedic boot, instrumented with a force sensor, is placed over the platform of the parallel robot with the aim of performing exercises for sprained ankles.

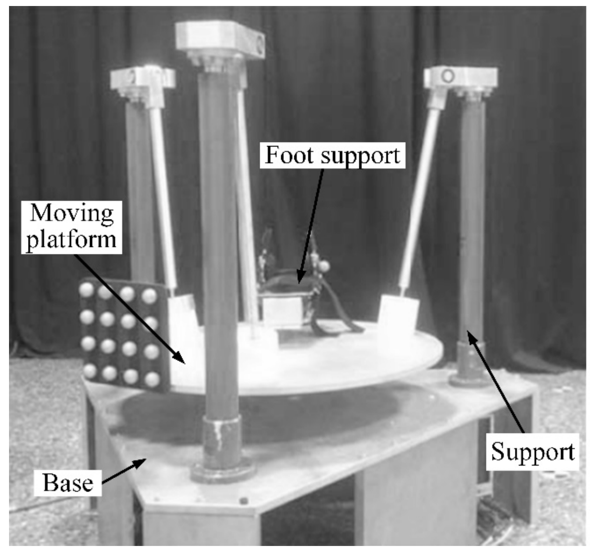

Fig. (35). The 3-PRS low-cost parallel manipulator.

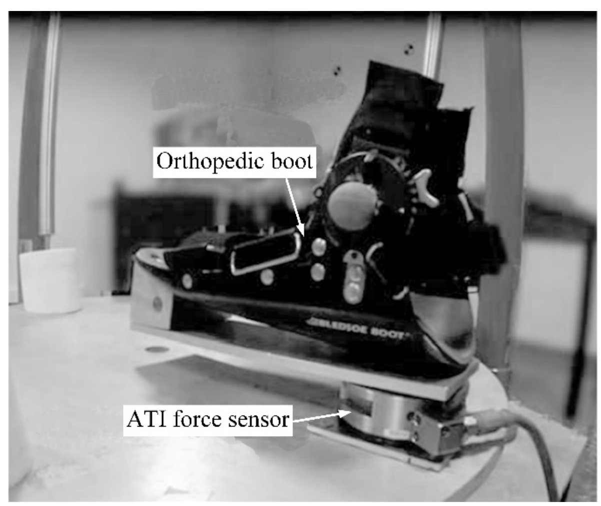

Fig. (36). Orthopedic boot.

A novel 3 DOF parallel robot was proposed by Ruiz-Hidalgo *et al*., which is shown in Fig. (**37**). Revolute and spherical joints are used in this ankle rehabilitation robot. This parallel robot is composed of five parts which are 3 electric actuators, 3 revolute joints, 3 spherical joints, a mobile platform and a fixed platform. The two actuators are installed in the opposite position. The axes of the revolute joints are installed parallelly [87]. The last actuator is installed in 90º. Turning the relation to the other actuators, the axis of the revolute joint is 90º. It can track the desired reference trajectory asymptotically.

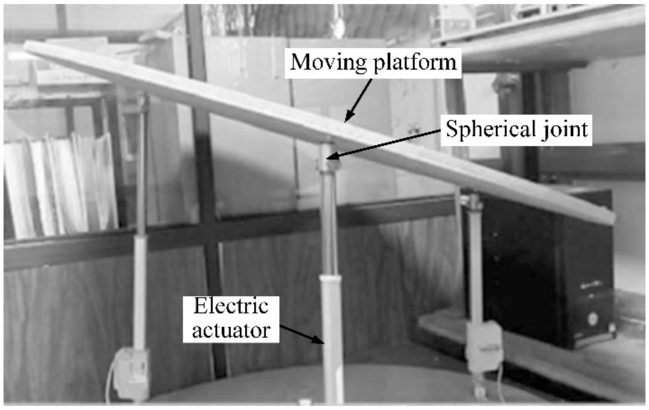

Fig. (37). A 3-DOF parallel robot for ankle rehabilitation.

Tsoi *et al*. designed three degrees of freedom parallel robot for ankle rehabilitation which is shown in Figs. (**38** & **39**). The vertical reaction force at the ankle is regulated through the using of the redundant actuation degree of freedom. In the situation of a spherical joint equivalent is used for connecting the upper actuator to the end effector, universal joints are used to connect the linear actuator to the base while [88-90]. Universal joints are used to connect the linear actuator to the base while a spherical joint equivalent is used for connecting the upper actuator to the end effector. This middle link is connected to the end effector through a spherical bearing to allow three degrees of freedom of rotation, thus allowing emulation of motion of the human ankle. This design allows the rotation center of end effector that coincides with the actual ankle joint and therefore makes the robot more suitable for ankle rehabilitation exercise.

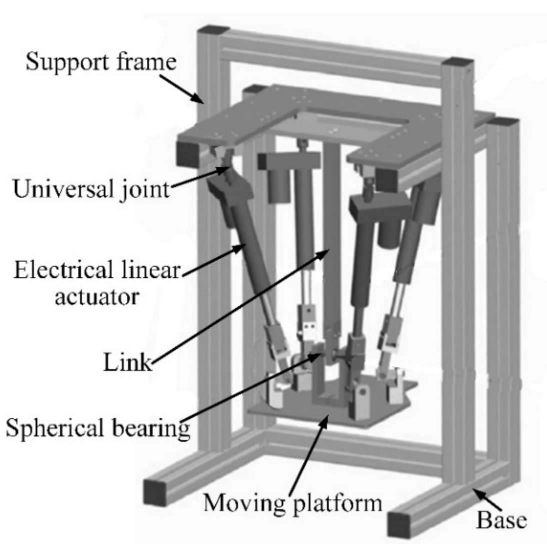

Fig. (38). Parallel robot for ankle rehabilitation.

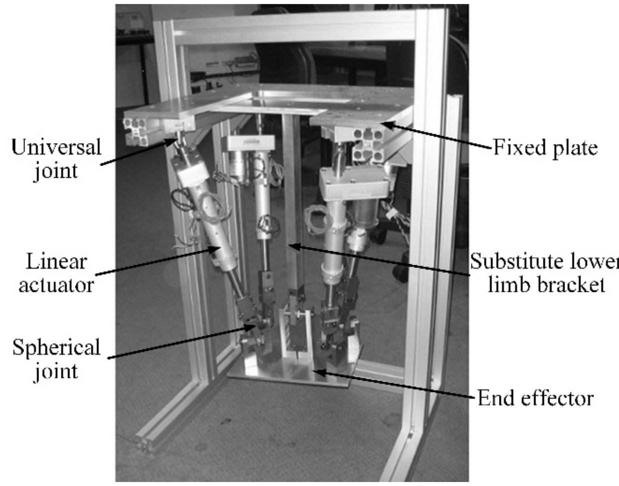

Fig. (39). Prototype of the ankle rehabilitation robot .

Zhou developed a rehabilitation parallel robot, which is shown in Fig. (**40**). It is mainly composed of a moving platform, static platform and six linear actuators [91]. The mechanism is driven by 6 cylinders. The connection between the moving platform and the linear actuator is connected by ball joints. The connection between the static platform and the linear driver is realized through the Hooke hinge.

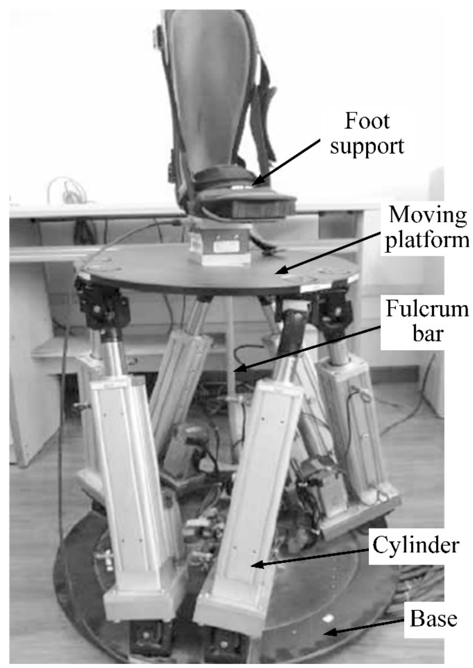

Fig. (40). Prototype of six degree freedom parallel robot.

3.4. Others Drive Type Ankle Rehabilitation Robot

Patoglu *et al*. from Sabanci University invented a reconfigurable parallel ankle rehabilitation device, which is shown in Fig. (**41**). It includes a moving platform and a base platform. The base platform and the moving platform are connected through the connecting member connects [92-94]. It comprises a joint member. The joint member is connected with the connecting member to the base platform. To realize the strengthening exercise, this device can cover the entire complex range of the body's ankle. During the balanced proprioception practice, it can also support body weight. The metatarsophalangeal joint practice can also be achieved through the reconfigurable design of the soleplate. The mechanism can be used as a clinical measurement tool. Horizontal motion of the ankle, force and impedance can be determined to help diagnose. It is ergonomic, lightweight and wearable. Because of its parallel kinematic structure and optimized bandwidth, the device has higher control performance than that of similar devices.

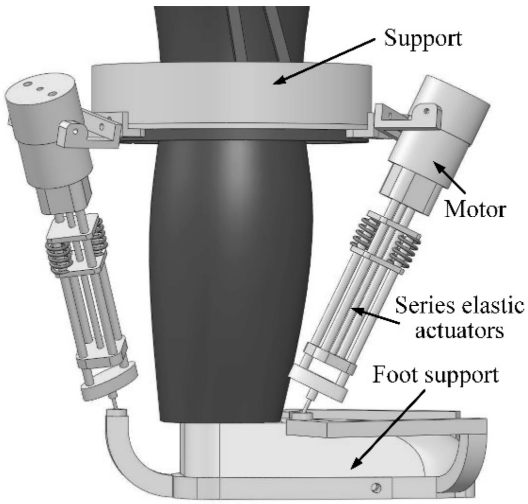

Fig. (41). A parallel ankle rehabilitation device.

Aggogeri *et al.* developed a modular mechanism system for ankle complex, which is shown in Fig. (**42**). It is composed of one motor that transmits power to both the left and right limb. To reduce the peak torque and improve the motor efficiency largely, a fluently engaged and disengaged parallel spring was incorporated at both joints [95]. To transfer energy from the knee to the ankle, an electrical energy transfer mechanism combined with an ultracapacitor is proposed. The device guarantees the repeatability of movement in particular for aged people. The patient can perform the rehabilitation exercise independently and easily, reducing the therapist's effort and guaranteeing the effectiveness of rehabilitation and safety.

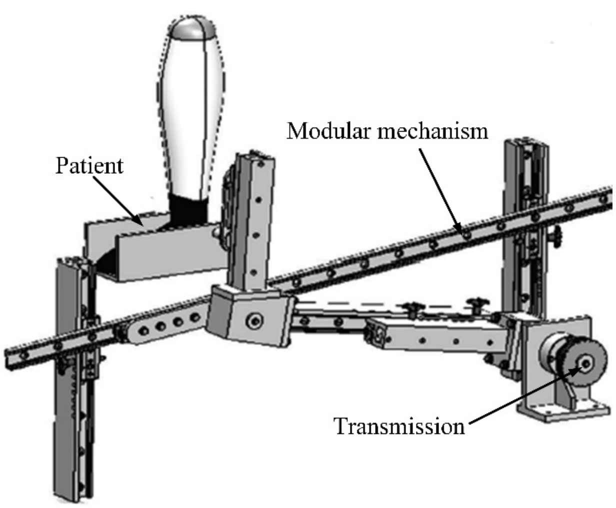

Fig. (42). Modular mechanism system for ankle complex.

Yu *et al*. developed a cable-driven parallel ankle rehabilitation mechanism, which is shown in Fig. (**43**). It includes the rack (including fixed platform), moving platform, restricted branch chain, guide pulley, rope tension detection mechanism, winch (winding rope mechanism), drive motor (including reducer) and drive rope [96]. One end of the 4 driving cables is connected with the moving platform, and the other end is connected with a winch driven by the motor by a guide pulley on the fixed platform and a rope tension detecting mechanism on the base. The rotation center of this structure and the ankle is consistent.

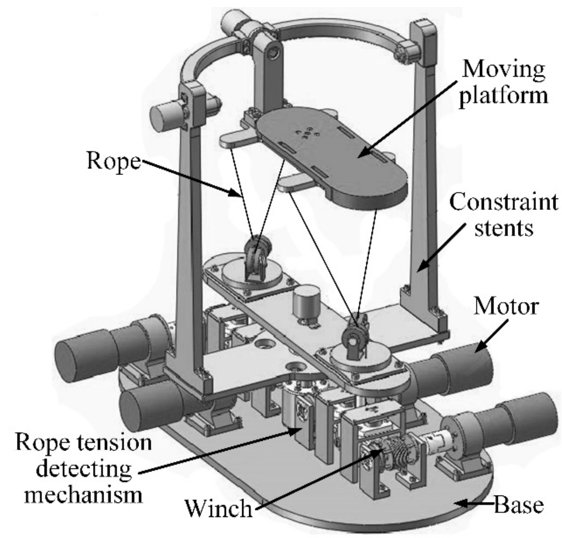

Fig. (43). Cable-driven parallel ankle rehabilitation mechanism.

The overview and classification of ankle rehabilitation robots are shown in Table **2**. As a whole, the structure of the motor-driven type ankle rehabilitation device is relatively complex, but it is easier to control. The pneumatic muscles type provides certain flexibility and it is friendly to the patients. The cylinder drive type has a better linear relationship, but it has big noise. There is also a new type of actuator, such as the SEA (Series Elastic Actuator). It can reduce resilience accordingly.

4. EXISTING PROBLEMS OF ANKLE REHABILITATION DEVICE

With the rapid development of rehabilitation medicine, rehabilitation robots are more widely used and their demand is increasing. Domestic experts and scholars are also actively studying ankle rehabilitation robot, but there are still many key technologies to be solved. At present, some problems still exist in the rehabilitation of the ankle joint:

(1) The rehabilitation training mode and training process are relatively simple, so the patient can easily feel bored and it is not conducive to arousing the patients' enthusiasm.

(2) The mechanical structure and control system of the rehabilitation equipment need to be improved. In the rehabilitation training, the angle, torque and speed of the joint are not controlled accurately. The rotary center of the device does not guarantee the reclosing of the gyration center of the ankle joint.

Table 2. Overview and Classification of Ankle Rehabilitation Robot.

Drive Type	Publication, Year	DOF, Structure	Characteristic	Code or Source
Motor Drive	Zhao *et al*., 2016 [16, 17]	3-SPS	Controlled conveniently, and the structure is simplified Provides three kinds of control: passive control mode, active control mode and impedance control mode The cost is reduced	References CN104068991
	Li *et al*., 2017 [18, 19]	3-UPS	The position of the human foot can be adjusted Simple structure, convenient use small occupation volume and low manufacturing cost	References CN105125380
	Li *et al*., 2014 [20-22]	3-RRR	The active, passive or semi-active rehabilitation modes of the ankle can be realized Compact structure	CN103070757 References
	Li *et al*., 2016 [23]	3-UPS	Avoid the singularity	References
	Zhang *et al*., 2015 [24]	3-RRR	The foot of the patient can be placed safely and reliably in the correct position Compact structure, good interchangeability Safety and reliability	CN104887452
	Cao *et al*., 2017 [25]	3-2R1T	The accompanying movement is eliminated fundamentally, and the secondary damage to patients can be prevented Good stability, manufacturing Assembly and maintenance simple	CN106983632
	Wang *et al*., 2015 [26-29]	3-RUS	Not only ensures the coincidence of rotation centers, but also constrains the orthogonality of the branched chain axes	CN103479502 References
	Wang *et al*., 2017 [30, 31]	3-RUS	Arrangement scheme of 4 RUS branch chains is adopted to ensure the good movement performance	CN106974805 References
	Wei *et al*., 2017 [32, 33]	3-RRR	Meet the requirement of the high flexibility and bearing capacity of the ankle Two models: exercise function training mode and muscle strength training mode	CN107050763 References
	Yao *et al*., 2015 [34-36]	3-PSP	Quick response to input and output It can be widely applied to clinical treatment and families, hotels, fitness places	CN103156756 References
	Malosio *et al*., 2014 [37, 38]	3-RRR	Designed according to Gosselin's robot Agile Eye	References
	Enferadi *et al*., 2016 [39, 40]	3-RSS	The rigid body can be rotated around a vertical axis by unlimitedly	References
	Ayas *et al*., 2017 [41, 42]	3-UPS	Redundantly actuated ankle rehabilitation robot Two models: passive and active ROM exercises	References
	Rosado *et al*., 2017 [43]	4-2-RRSP	Easy to program	References
	Li *et al*., 2017 [44, 45]	3-UPR	High stiffness	References
	Du *et al*., 2017 [46]	3-RRS	Clinical treatment and ankle muscle relaxation	References
	Zeng *et al*., 2015 [47]	3-UPS	The decoupled parallel ankle rehabilitation robot easy to machining control simple	References
	Sun *et al*., 2016 [48]	5-RRS	The equipment to move smoothly and stably	References
	Wei *et al*., 2016 [49]	6-UPS	Small in size, low-weight and high adaptability	References

Table (2) Contd….

Drive Type	Publication, Year	DOF, Structure	Characteristic	Code or Source
	Nurahmi *et al*., 2017 [50]	3-RPS	The structure is light and match with the ankle joint	References
	Han *et al*., 2015 [51]	3-RUPS	Compact structure High bearing capacity The control is simple	References
	Li *et al*., 2015 [52]	3-UPS	Three axes ankle rehabilitation movement	References
Pneumatic Muscle Drive	Zhang *et al*., 2017 [53-60]	3-RPS	Good flexibility and strong adaptability	CN105105970
	Liu *et al*., 2017 [61]	3-UPS	High rigidity, high response and no cumulative error of the parallel mechanism Good flexibility, safety and pollution-free	CN105943306
	Jamwal *et al*., 2018 [62-73]	3-UPS	Adapts to different patient's feet	References
	Cao *et al*., 2016 [74]	3-UPS	Flexible drive of pneumatic muscles; nonlinear motion	References
Linear Cylinder Drive	Yonezawa *et al*., 2015 [75]	6-UPS	Complex movement ability Measurement of motion data Feedback in real time	References
	Nomura *et al*., 2016 [76,77]	6-UPS	Modularization, remote control, low cost Passive exercises and walking prevention	References
	Rastegarpanah1 *et al*., 2016 [78,79]	6-UPS	The bearing capacity is good It can follow the track of the foot very well	References
	Vallés *et al*., 2017 [81, 82]	3-PRS	Passive exercise Active-assistive exercise Active-resistive exercise	References
	Ruiz-Hidalgo *et al*., 2016 [83]	3-UPS	The noise is loud	References
	Tsoi *et al*., 2016 [84-86]	3-UPS	Avoid the singularity	References
	Zhou *et al*., 2015 [87]	6-UPS	The space position and posture of the motion platform can be changed	References
Others Drive	Patoglu *et al*., 2017 [88-90]	3-UPS	It is ergonomic, lightweight and wearable higher control performance than that of similar devices	References
	Aggogeri *et al*., 2016 [91]	3-UPS	Patient can perform the rehabilitation exercise independently and easily, reducing the therapist's effort and guaranteeing the effectiveness of rehabilitation and safety	References
	Yu *et al*., 2015 [92]	3-RRS	The rotation center of the device and the ankle are coincident	References

(3) The portability of the rehabilitation device is poor and the volume is large. Its safety and adaptability also need to be improved.

(4) The feedback mechanism of the effect of rehabilitation training needs to be improved.

(5) The movement and force of the ankle are relatively complex, and the muscles and tendons are intricate. Therefore, there are still many challenges in many fields of technology.

CONCLUSION

In this paper, representative ankle rehabilitation robots and related equipment are discussed. Based on different drive types, ankle rehabilitation robots are classified into motor drive type, pneumatic artificial muscle and pneumatic cylinder drive type and other drive types. Structural characteristics, rehabilitation training mode and applications of different types of ankle rehabilitation robots are summarized. This paper concludes that the motor drive type robot is characterised by simple structure, high reliability, easy operation and high control accuracy. However, this type of ankle rehabilitation robot is lack of flexibility. Thus, it has a certain security risk for patients. Pneumatic cylinder and pneumatic muscle drive type robot have the advantages of good flexibility and low noise. This paper will bring meaningful reference for the development of ankle rehabilitation robots. We will focus on reviewing and discussing mechanical design, safety, virtual reality, brain-computer interface, control strategies and algorithms of Bio-syncretic mechanism system ankle rehabilitation robot in the future study.

CURRENT & FUTURE DEVELOPMENTS

At present, the ankle rehabilitation robot can provide a simple training program for the patients to a certain extent, and it has a certain effect on rehabilitation. In view of the current literature and clinical requirements, future research on ankle rehabilitation robots should be carried out according to the following aspects:

(1) The design of the mechanical structure of the ankle rehabilitation robot is the basis of the functional rehabilitation training robot system. Easy, freedom, flexible, and varied training exercises are necessary. As for the structure, we need to meet the center of rotation of the ankle joint and the center of rotation of the mechanism to precisely control the motion parameters such as the angle, torque and speed of the ankle joint. The calf part should be fixed, with the adjustment of the distance and the adjustment of the sitting position. It can have the function of massage on the chair. It can also relax the body and mind at the same time during the rehabilitation treatment. Therefore, the physiological pressure and psychological pressure of the patient are relieved.

(2) The design of the movement mode and control strategy of the ankle joint rehabilitation robot: The designed robot should be able to perceive the state information (force and position) of the ankle. The corresponding training mode and control strategy are adopted because of the difference existing in the patients' condition. The adaptability and stability of the control system, the use of sensor technology and the design of control algorithms should be studied. The software should have good programmatic, friendly interface features, and simple and interesting games. By the use of virtual reality technology, the device can provide real-time feedback, design personalized training programs, and build a rich virtual environment. Therefore, this design increases the mission's interest and greatly increases the patients' initiative in participating in the rehabilitation training to better promote the recovery of a sports function.

(3) Force feedback and position feedback: The ankle rehabilitation robot should be able to detect and perceive the interaction between the ankle and the device in real time, as well as the position information of the ankle. The ankle rehabilitation robot should be able to detect and perceive the interaction between the ankle and the device in real time, as well as including the position information of the ankle. Through the expert system, the specific track of the rehabilitation movement is planned on the computer screen, so that the track of the ankle joint is as close as possible. In this way, better therapeutic and rehabilitation results can be achieved.

(4) Security protection: The security problem is always an important aspect of the design of the rehabilitation robot. The design must conform to the basic movements and safety requirements of clinical rehabilitation training. In addition to achieving rehabilitation training, we also need to prevent the occurrence of two injuries. This requires structural design (hardware) and control system (software) design to ensure patients' safety.

(5) Evaluation mechanism of rehabilitation effect: Through the combination of EMG or EEG (Electroencephalograph) detection, the internal relations and rules of the rehabilitation effect and the training parameters are explored. Remote assistance technology enables patients and doctors to communicate in real time, thus improving the rehabilitation training program, saving cost and improving efficiency. Remote rehabilitation makes the rehabilitation site no longer limited to hospitals and increases the utilization of resources. During the rehabilitation training, it is realized from passive to active state.

As a new form of rehabilitation, Bio-syncretic mechanism system (BSMS) has strong practicability and adaptability. It is a rehabilitation system composed of organism and machinery. The organism is bound to the mechanical mechanism, and the organism is a necessary part of the rehabilitation organ to realize the motion determination. At the same time, the mechanical part cannot be independent of the organism and its movement is a rehabilitation mechanism that is the result of the joint action of the machinery and the organism. Compared with the traditional passive rehabilitation mechanism, this mechanism will be the individual difference of the patient into the rehabilitation agencies to improve the adaptability of rehabilitation equipment, more conducive to the promotion of rehabilitation equipment.

LIST OF ABBREVIATIONS

BSMS	=	Bio-Syncretic Mechanism System
CPM	=	Continuous Passive Motion
DOF	=	Degree Of Freedom
EEG	=	Electroencephalograph
EMG	=	Electromyogram
FP	=	Fixed Platform
GUI	=	Graphical User Interface
MP	=	Moving Platform
PID	=	Proportional Integral Derivative
PMA	=	Pneumatic Muscle Actuator
PMs	=	Parallel Manipulators
ROM	=	Range Of Motion
SPM	=	Spherical Parallel Manipulator
SEA	=	Series Elastic Actuator

CONSENT FOR PUBLICATION

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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