MAJOR TRENDS IN THE DEVELOPMENT OF ANKLE REHABILITATION DEVICES

PRINCIPALES TENDENCIAS EN EL DESARROLLO DE DISPOSITIVOS DE REHABILITACION PARA TOBILLO

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ABSTRACT: In this paper the evolution of industrial robotics towards rehabilitation tasks is addressed. The importance of ankle injuries and the appropriate passive or active rehabilitation procedure is also highlighted. The ankle rehabilitation devices reviewed include those already commercially available and those at a development stage in laboratories and research centers. At the end of the paper there is a proposal about developing a mechatronic device, of medium complexity, for ankle rehabilitation, focused on active rehabilitation with some particular features.

KEYWORDS: Robotics, ankle rehabilitation, active rehabilitation, mechatronic device.

RESUMEN: En este artículo se aborda el tema relacionado con la evolución de la robótica industrial orientada a tareas de rehabilitación. La importancia de las lesiones de tobillo y su adecuado procedimiento de rehabilitación pasiva o activa, es también considerada. Se han revisado los dispositivos de rehabilitación del tobillo, tanto los que ya están comercialmente disponibles como aquellos en etapa de desarrollo en laboratorios y centros de investigación. Al final de este artículo se propone la posibilidad de desarrollar un dispositivo mecatrónico, de complejidad intermedia, para rehabilitación del tobillo, orientado a la rehabilitación activa y con algunas características particulares.

PALABRAS CLAVE: Robótica, rehabilitación de tobillo, rehabilitación activa, dispositivo mecatrónico.

1. INTRODUCTION

During approximately the last 50 years, robotics research has been aimed at finding solutions to technical necessities of applied robotics. The evolution of application fields and their sophistication have influenced research topics in the robotics community. This evolution has been dominated by human necessities. In the early 1960s, industrial robots were put in factories to replace the human operator in risky and harmful tasks. The later incorporation of industrial robots into other types of production processes added new requirements that called for more flexibility and intelligence in industrial robots. Currently, the creation of new needs and markets outside the traditional manufacturing robotics market (i.e., cleaning, construction, shipbuilding, agriculture, mine clearance, teaching, learning) and the aging population in certain countries, is demanding field and service robots to attend to the new market and to human social needs [1-5].

For several decades there has been a great interest in the science and technology community to develop devices that are of practical value to society as a whole, one of the most promising areas is assisted rehabilitation robotics systems, particularly as this is driven both by the need for timely care for people who require the appropriate therapy and by technological advances that are generated.

Since the 1960s [6] the activity in rehabilitation robotics began and it has slowly evolved through the years to a point where the first commercially successful products are now available. Today, the concept of "rehabilitation robot" may include a wide array of mechatronic devices ranging from artificial limbs to robots for supporting rehabilitation therapy or for providing personal assistance in hospital and residential sites.

Examples include robots for neuro-rehabilitation [7], power-augmentation orthosis [8], rehabilitative orthosis, prosthesis [9], etc.

The field of rehabilitation robotics is less developed than that of industrial robotics. Many assistive robotics systems have featured an industrial robot arm for reasons of economy and availability [10]. However, the specifications for robots in these two application areas are very different. The differences arise from the involvement of the user in rehabilitation applications. Industrial robots are typically powerful and rigid to provide speed and accuracy. They operate autonomously and, for reasons of safety, no human interaction is permitted. Figure 1 summarizes the evolution of robotics research over the last 50 years [1].

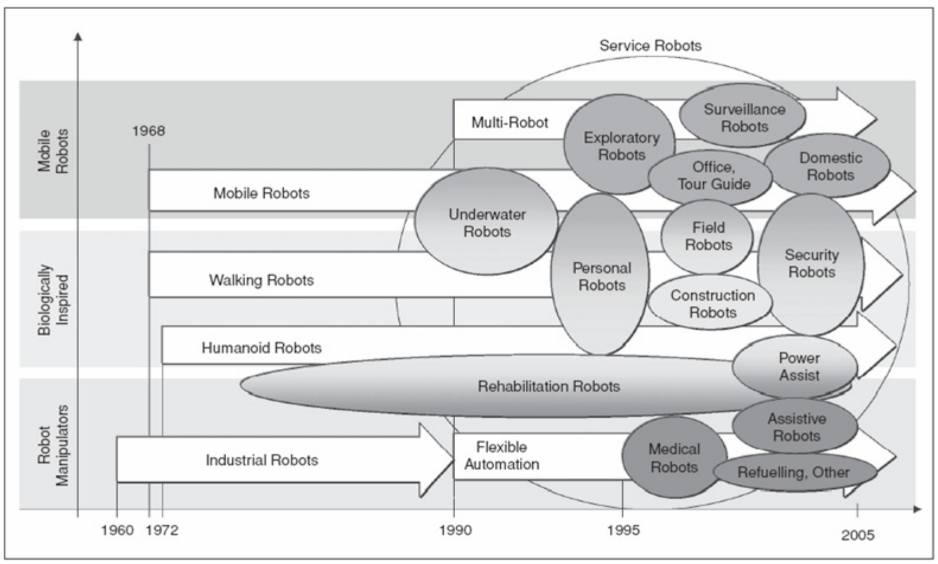

Figure 1. Time evolution of robotics research toward service robots [1]. Copyright IEEE. Reprinted with permission.

2. THE IMPORTANCE OF ANKLE INJURY

Humans are occasionally at risk of suffering traumatic incidents in the upper and lower extremities, which sometimes cause permanent muscle injury preventing people from performing certain daily activities. In addition, there are several neuromuscular diseases that require immediate treatment in order to avoid more severe or permanent damage [11].

Ankle sprain is a serious injury, its frequency is approximately between 15 and 20% of all sports injuries, according to different publications, and is the most common in traumatic emergencies.

A sprained ankle can occur to athletes and non-athletes, children and adults. It can occur when a person takes part in sports and physical fitness activities. It can also occur when a person simply steps on an uneven surface, or steps down at a certain angle. For example, lateral ankle sprains are very common among basketball players and are responsible for a large amount of time lost in rehabilitation [12-17].

Ankle sprain occurs when the ankle is turned unexpectedly in any direction that is further than the ligaments are able to tolerate, with the most common being due to hyper inversion (Figure 2), which damages the lateral ankle ligaments [14]. Ankle sprain can be classified clinically into 3 grades: grade I involves stretching of any ligament; grade II includes incomplete tearing of one or more ligaments; and grade III includes complete tearing of one or more ligaments [14, 17, 18].

Although mild ankle sprain (grade I) responds well to conservative treatments and recovers back to normal levels within 2–3 days, more than 40 percent of moderate to severe ankle sprains lead to recurrence, chronic ankle pain, complex regional pain syndrome, joint instability or joint stiffness [17,19,20]. In spite of this kind of joint disability, the lack of significant differences in some studies, in mechanical laxity over an 8-week period suggests that natural recovery of laxity takes longer than 8 weeks [21].

If a person has sprained their ankle in the past, they may continue to sprain it, if the ligaments did not have enough time to completely heal. If the sprain happens frequently and pain continues for more than four to six weeks, a chronic ankle sprain may occur. Activities that tend to make an already sprained ankle worse include stepping on uneven surfaces, cutting actions and sports that require rolling or twisting of the foot, such as trail running, basketball, tennis, football and soccer [13].

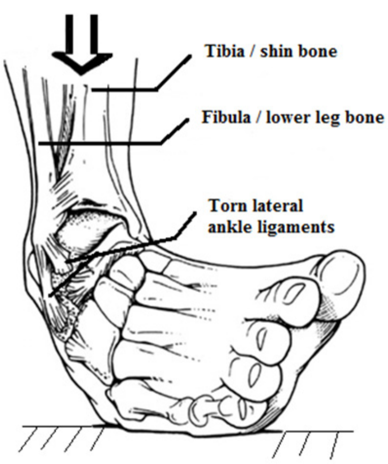

Figure 2. Ankle sprain.

3. TREATMENT AND REHABILITATION OF THE ANKLE

Rehabilitation, in a general sense, is the process by which, through physiotherapy it is possible to recover physical abilities lost due to a traumatic incident.

The objective of rehabilitation is to regain full function without limitations, especially for athletes who need to return to the same level of physical fitness. If this is not possible, we try to achieve the ability to perform as many daily activities as possible.

We can consider four types of recovery stages depending on the level of the patient's activity: passive, assisted, active free, and active resisted [22]. In "passive recovery" there is a professional therapist or a device that mobilizes the structures without the patient's effort. When the patient is involved in the effort of developing the exercises, the recovery is called "active". An intermediate form is "assisted" in which the effort combines patient and therapist or assisting device activities. Active free is when the patient moves his ankle by himself without any kind of opposing force; it is considered as active resisted when the patient moves his ankle and there is an opposing force (from a therapist or from a device).

Treatment of an ankle injury could be divided into three phases: the initial phase, rehabilitation and the functional phase [23, 24]. The duration of each phase depends on the individual healing process.

The initial phase includes analgesic and antiphlogistic effects and the reduction of swelling. This is achieved by rest, elevation, ice in combination with compression, ultrasound and electrotherapy, as well as oral treatment with non-steroidal anti-inflammatory drugs and enzymes. To preserve neuromuscular coordination, it is necessary to start gait training—without weight bearing—as soon as possible.

The rehabilitation phase is intended to increase motion and strength. This increased activity should facilitate the circulation and promote elimination of residual inflammatory agents. In the early phase of rehabilitation vigorous exercise is discouraged. Proprioceptive (related with one's inner perception of our body status) exercises can be put in practice at the beginning of this stage to limit proprioceptive loss. The injured ligament must be maintained in a stable position so that healing can occur. Partial weight bearing with crutches helps to control several complications related to healing. Muscle atrophy, proprioceptive loss and circulatory stasis are all reduced when even limited weight bearing is allowed. Weight bearing also inhibits contracture of the tendons, which can lead to tendinitis. For these reasons, early ambulation is essential, even if only touchdown weight bearing is considered. The range of motion (ROM) exercises beginning with plantar and dorsal flexion can be implemented from the beginning. As swelling and pain diminish, inversion and eversion exercises can be made with manual mobilization; strengthening of the muscles may be carried out by a progression of isometric and isotonic exercises to isokinetic as the intensity of pain diminishes.

The functional phase prepares for a return to full activity and includes jumping and running as well as isokinetic exercises. In the past, athletes were simply returned to sports once the pain was low enough to tolerate the activity. Returning to full activity should include a gradual progression of functional activities that slowly increase the stress on the ligament. The specific demands of each individual sport dictate the individual drills of this progression. The athlete should have complete range of motion and at least 80 to 90% of pre-injury strength before considering a return to the sport. Finally, if full practice is tolerated without any pain in the injured part, the athlete may return to competition [24].

Currently, most centers have some limitations in the service that can provide to patients requiring rehabilitation, since they have few staff, the therapist can apply sudden movements for various reasons (fatigue, carelessness, etc..) causing pain in the affected part, so the availability of ankle rehabilitation devices that could assist therapists in the development of their work is considered to be very useful.

4. ANKLE REHABILITATION DEVICES ON THE MARKET

4.1 Low complexity devices

Devices used in ankle rehabilitation could be very simple; such as elastic bands, roller foams and wobble boards. These devices are typically used in exercises that could be performed both in clinic or at home, they are easy to find in almost any physiotherapist shop; they are usually intended for functional rehabilitation. Elastic bands are the simplest devices, made of multi-shaped strips of resistive elastic intended for muscular strengthening. Roller foams act as unstable surfaces and are used to improve balance and proprioception. Wobble boards are circular discs with a hemispherical pivot in the center of one of the sides, used to improve balance and proprioception too (figure 3) [25-28].

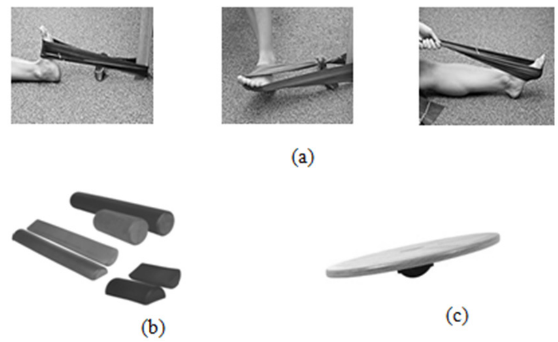

Figure 3. Some exercises with elastic band (a); roller foams (b); wobble board (c).

4.2 Intermediate complexity devices

Recently, in order to assist and improve the process of ankle rehabilitation, some firms have developed several commercial electromechanical systems that allow patients to move and stretch the muscles and tendons gently [29-33]; usually their movements are similar to the basic ankle movements (figure 4), being able to obtain different ROM (measured in degrees) and various angular velocities (measured in degrees/s) for each rotation axis considered.

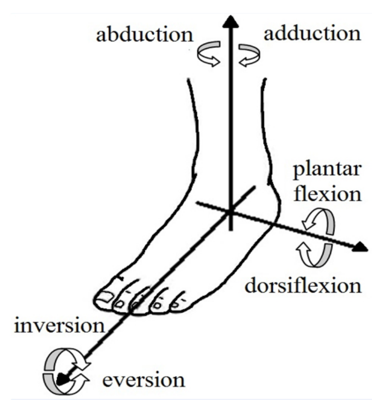

Figure 4. Basic ankle movements.

These machines, in a general sense, are good in helping the rehabilitation ankle process, focusing in range of motion restoration and improving the flexibility of the ankle muscles. Nevertheless, they have some limitations or drawbacks; maybe the most important disadvantage is that nowadays they work in a Continuous Passive Motion (CPM) basis, in which the patient plays a rather passive role in the rehabilitation process. Another usual limitations consist in working only with constant angular velocities, performing only basic ankle movements without accomplishing more complex movements (e. g. different useful combinations of basic ankle movements), besides some of them are quite expensive. The cost of the device is usually directly related with its capacity, e. g. the more different possibilities in axis rotation (number of degree of freedom, DOF), greater ROM and diversity in angular velocities, the more expensive.

Figures 5 and 6 show some commercial systems offered on the market for helping with and promoting ankle rehabilitation; in both cases the patient could either be in a sitting or a lying position.

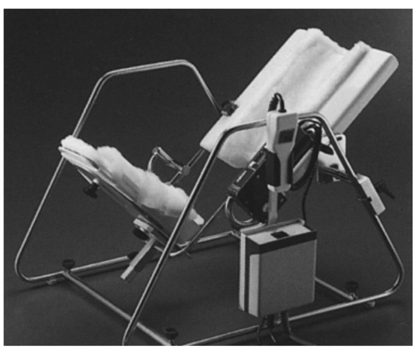

Figure 5. JACE Ankle A330 CPM system, one DOF [29]. Photo courtesy of JACE systems.

Figure 6. Optiflex Ankle CPM system, two DOF [30]. Photo courtesy of Chattanooga Group.

4.3. High complexity devices

There are also high-complexity commercial developments not only for helping in ankle rehabilitation but to promote rehabilitation in the entire lower limbs, examples of these systems are some products from Biodex (figure 7) [34, 35] and Lokomat [36, 37]. These sorts of systems have high capabilities for data acquisition, storage, transmission and written reports elaboration, allowing objective evaluation in patient progress throughout the rehabilitation therapy. Some of the disadvantages of these products consist in being expensive, bulky, needing a specialist who operates the systems and obviously are only suitable for clinical use.

Figure 7. Biodex Multi-Joint System 4 Pro (a), in ankle therapy (b), [35]. Photo courtesy of Biodex Medical Systems, Inc.

5. SOME ANKLE REHABILITATION PROTOTYPES

Recently there has been great interest in some research centers around the world to propose and develop automated systems for ankle rehabilitation [22, 38-50]. Much of the work focuses on the limitations of existing commercial rehabilitation devices, i.e. obtaining combinations of basic ankle movements, planning trajectories and velocities, development of databases with records of the initial state of the injured ankle and its evolution in the rehabilitation process. A very important aspect is the incorporation of the function to strengthen the muscles and tendons of the ankle trough active rehabilitation. In some cases, virtual reality environments have been proposed to make the rehabilitation program interactive and more interesting.

We could find extensive information about several devices offering ankle rehabilitation; in some cases there are good ideas expressed in drawings and schemes of mechanisms or machines, in other cases there are CAD models or even virtual models dynamically analyzed with some advanced software tools (e.g. ADAMS). Among those, in [51] the authors propose a virtual prototype of an ankle rehabilitation machine which provides the whole range of ankle related foot movements (3 DOF). There, a PID and a computed torque controllers were designed to meet the trajectory tracking task, providing smooth movements for rehabilitation in a single motion or the combination of two movements, respectively. Simulation results using the mathematical model were presented and compared with the virtual prototype obtained from simulations using the ADAMS environment.

Sometimes we could find developed and tested prototypes. Below some of the prototypes recently developed for passive and active rehabilitation of the ankle are discussed. The Rutgers Ankle robot manipulator [52-59] is based on a Gough-Stewart platform. It can generate rotation and translation (6 DOF) within its workspace, it is part of an orthopedic rehabilitation system (Telerehabilitation with Virtual Force Feedback, see Figure 8) which has prototypes for hand, elbow and knee rehabilitation. This system includes visual and audio stimuli (playfulness) with various programs that allow the patient to exercise with the help of simulations in virtual reality environments. It also includes computer programs capable of capturing information that can measure the degree of progress of the patient, the final stages of the project extended the system to two platforms with the intention of including proprioception exercises as well as gait rehabilitation. The ability to perform monitoring and data acquisition via Internet has been included. This system has been tested successfully in several pilot clinical trials including proof of concept, orthopedic rehabilitation, post-stroke rehabilitation and rehabilitation of musculoskeletal injuries.

It is remarkable that despite the efforts devoted to Rutgers Ankle in terms of organizational infrastructure, physical and human resources for over 10 years of research, currently there seems to be no product on the market that directly comes from this technology development effort, thus confirming the various comments about the difficult process for incorporating and using robotics mechanisms within the work environment of the medical community and health professionals [38, 39].

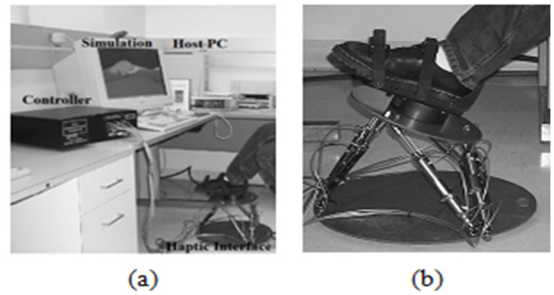

Figure 8. The “Rutgers Ankle” Orthopedic Rehabilitation System (a), the Haptic Interface (b) [52]. Copyright ASME. Reprinted with permission.

The 3-RSS/S parallel robot for ankle rehabilitation [22, 40], developed by G. Liu, J. Gao et al. can provide rotational movement around three orthogonal axes. It is based on a Rotational-Spherical-Spherical/Strut mechanism. The function of the strut is to restrain and support the top platform (see figure 9). Authors emphasize that this prototype rotary actuator is better than the prismatic device when the patient moves the manipulator (back-drivability) and is generally more appropriate for the rehabilitation of the ankle. Future work is reported as adding internet communication to diagnostic and assessment work, as well as the inclusion of elements of virtual reality.

Figure 9. 3-RSS/S Ankle rehabilitation parallel Robot. Copyright IEEE. Reprinted with permission.

Another recently developed prototype for passive and active ankle rehabilitation was proposed by J. A. Saglia et al. [41, 42]; it is an ankle rehabilitation device based on a 2-DOF, redundantly actuated parallel mechanism (figure 10). The proposed parallel mechanism has the advantage of mechanical and kinematic simplicity when compared to existing platforms while at the same time it is capable of carrying out the main exercises required for ankle rehabilitation, based on dorsi dorsi/plantar flexion and inversion/eversion movements. The device makes use of actuation redundancy to eliminate singularity and improve the workspace dexterity. The rehabilitation protocol has been considered as the basis for the design of control strategies. Both patient-passive and active exercise types have been addressed using position and admittance control strategies.

Figure 10. Prototype of 2 DOF over-actuated ankle rehabilitation robot [41]. Copyright IEEE. Reprinted with permission.

6. OUR PROPOSAL

Our proposal is to design and build a machine of intermediate complexity for rehabilitation of muscles in ankles, for people who have some physical disease, or who have suffered a traumatic incident related to the ankle. It is intended for the system to give integral rehabilitation therapies to patients who have some kind of injury in the ankle, through controlled movements and forces. In addition, it will increase the length of service for therapies and will reduce the work of the therapists at rehabilitation centers.

With feedback from sensors the rehabilitation device will prevent sudden movements, so controlled and smooth movements will be provided to avoid further lesions to the injured part. Using a trajectory planning of smooth and bounded movements, the corresponding bounded control signal will prevent the patient from an abrupt movement that could worsen their recovery status. Active control of this machine will produce an opposing force to the movement, contributing to the strengthening of the injured part for total rehabilitation, i.e., it will have impedance control, resulting in a continuous active motion machine.

The prototype to be developed for ankle rehabilitation consists of a mechatronic device with the following features:

1. Portable. The rehabilitation machine will be portable, allowing home therapies as patients are not always able to move to a rehabilitation center to receive therapy.

2. Versatile. The machine will have the capacity to implement a variety of therapeutic exercises for a range of patients with different traumatic problems.

3. Adaptable. This refers to the feature of being adjustable to the size of different people.

4. Economic. The device, due to its life span and capability to provide physiotherapy services, will be able to help therapeutic personnel in their labor. This allows them to develop other tasks, resulting in time and cost savings.

5. Social impact. There is the expectation that it will reduce the recovery time of people who have suffered traumatic incidents related to ankle injury by increasing the patient's therapy sessions [7, 42]; the device will be able to provide up to 15 minutes of continuous sessions, determined by the therapist.

6. Simple. The design is based on the model of the lower limb of the human body as a system of three links and two joints, providing the two main rotations of the foot; plantarflexion/dorsiflexion and inversion/eversion.

7. In addition, the device will be based on the mode of **continuous active motion (CAM)** by which the patient can not only recover their mobility, but can also strengthen the affected muscles, with a complete ankle recovery.

8. The physical part of the device is intended to be based on a parallel robot with a 2 closed kinematic chains mechanism with Revolute-Revolute-Spherical/Strut joints (2RRS/S), the general appearance of the prototype is shown in Figure 11.

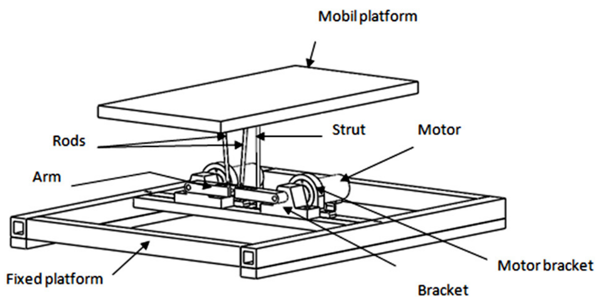

Figure 11. Ankle rehabilitation prototype based on a 2-RRS/S mechanism

7. SUMMARY

In this paper we have reviewed the evolution of industrial robotics towards service robotics as a result of attention to social needs and new markets, emphasizing the appearance of robotics in rehabilitation, which has gradually advanced and now the current production of some commercial products is a fact. The importance of ankle injuries is due mainly to its high degree of occurrence and because, if not treated promptly, it may result in severe and permanent injury that negatively affects the quality of life of patients. Rehabilitation may be considered passive or active depending on the degree of effort of the patient. The active mode is desirable because it includes the strengthening of the tendons and muscles of the ankle, allowing the possibility of recovering pre-injury status. It is common for centers in the health sector to have some limitations that prevent proper care for patients in general and in particular to those requiring rehabilitation with ankle therapy, hence the convenience of developing devices for rehabilitation.

Currently there are several devices on the market that help to rehabilitate the ankle; they may be of low complexity (elastic bands, foam rollers and wobble boards), of intermediate complexity aimed to regain ROM and elasticity of the injured parts and are usually the Continuous Passive Motion type, and high complexity devices, usually very complete, bulky and expensive, so they can only be used in clinical settings.

Recently there has been a great interest in some research centers around the world to propose and develop automated systems for ankle rehabilitation. A very important aspect is the incorporation of the function to strengthen the muscles and tendons of the ankle through active rehabilitation; the proposed devices vary from one to six degrees of freedom.

In the last part of the paper the development of a prototype is proposed, it is expected that the prototype will accomplish several favorable features for ankle rehabilitation. The model of the human lower limb will be considered as having 2 DOF [60] and hence the prototype will have dorsiflexion/plantarflexion and inversion/eversion movements.

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