Design of a mechanical system in gait rehabilitation with progressive addition of weight

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Abstract. In this paper we designed and developed a mechanical device for gait rehabilitation based on the application of "partial body weight reduction therapy". An evaluation of the characteristics of devices based on this therapy currently available on the market was carried out obtaining information of the different mechanisms used in it. The device was designed to adapt to different height and weight of patients and to be used with additional equipment in gait rehabilitation, for example, treadmills, elliptical trainers and vertical scalers. It was envisaged to be used by patients with asymmetry in the lower extremities capabilities. We developed a stable structure in steel ASTM A36 which does not depend on the building conditions of the installation site. RamAdvanse software was used to calculate structural stability. A winch with automatic brake mechanism was used to raise/lower the patient, who was tied to a comfortable harness which provided safety to the patient and therapist. It was possible to quantify precisely, using counterweights, the weight borne by the patient during therapy. We obtained a small-sized and ergonomic low-cost prototype, with similar features to those currently considered cutting-edge devices.

1. Introduction

Walking is an essential daily activity carried out by any person to perform many activities independently. In normal conditions, gait is an automatic activity. Walking and weight bearing are the most important functions of the lower limbs, which must be considered in rehabilitation when gait is abnormal. Rehabilitation programs try to achieve the patient's recovery to a position of balance and ability to walk normally in a phased manner.

Patients with gait disorders due to different lesions often show great difficulty to support the body weight on the affected members, by abnormal patterns of motion, muscle weakness, or others.

In the past, the recovery of motor control was achieved by moving the segments involved with the help of a therapist who gradually introduced small resistances in order to enhance certain muscle groups which were already active. This traditional approach, which is still currently applied, was further enhanced after 1960 by neuromuscular and neurophysiological methods, which are based on the use of reflexes and sensory stimuli to stimulate or inhibit a particular motor behavior. Currently there are several methods that differ in the hierarchical CNS (Central Nervous System) approach and interactions with the periphery and muscles.

Today [1] the approach known as "task-oriented"[2], disconnected from the "practice of functional tasks" seeks to go beyond the concept of hierarchical organization of CNS and explain the control of all motor behaviors considering it like a systematic interaction in which there would be a multi-system
control, exerting influence in parallel in order to perform a specific task. This means that it would not only be the CNS but also other systems such as muscle-skeletal and external environment which would influence motor behavior and therefore it would be taken into account in treatment. It also attempts to associate this idea of multisystem organization with the latest learning theory. Also it questions the assertion that "more training is better" and attests the fact that training is beneficial as long as it produces a beneficial change that addresses the functional purpose of diminishing some of the disabilities that the patient presents [1].

It has been suggested that "task oriented" rehabilitation should not be delayed, as in other methodologies, until the patient has got a good head, trunk in sitting and standing control, and also until abnormal reactions have disappeared and the spasticity has been controlled. Task-oriented techniques ensure that gait is an automated functional activity which can and should be trained at an early stage even in the absence of the conditions described above [1-2].

The most prominent gait rehabilitation in the current investigation into the technical "task-oriented" is "body partial weight reduction therapy" while walking on a treadmill. This is a relatively new technique that originated from the investigation of neural locomotion control of the vertebrates. Based on observations and the result of experimentation of this technique in cats [3-5], a number of research teams around the world began to test the therapy on humans [6-9].

This therapy is based on the combination of two elements:
1. A postural control device which reduces the amount of weight borne by the patient.
2. A treadmill which moves at a slow speed to retrain the appropriate patterns for better gait.

Several studies have shown that partial body weight support on a treadmill can improve walking in patients with spinal cord injury [10-14].

In recent years various devices that meet the requirements of this therapy have been developed. Some of those are the “biodex weight reduction system” [15], “pneumexpneu-walker” [16], “project walk equipment” [17] and “lokomat” [18], among others.

Some of these devices do not allow for a comfortable rehabilitation, nor do they have the ability to quantify the weight borne by the patient, and accessibility to patients is limited, which prevents the patient’s proper rehabilitation. Devices of this type that have all the appropriate features for gait rehabilitation have a high cost for the Latin American market.

In this work we designed a prototype for proper gait rehabilitation and for accurate quantification of the patient's weight which is supported on their lower limbs. Ergonomic and economic aspects are conditions that were considered in this device to ensure that these therapies are easily available to the society.

2. Design of the Device

The design of the device comprises gait rehabilitation of many disabilities, using the “body partial weight reduction therapy”. We developed a completely mechanical design, easy to manipulate and economically viable to start mass production.

The device was designed in a modular format that covers the structure, the counterbalance system of the patient, the lifting system and the patient's harness, which act together to achieve the goal effectively. This feature of modularity allows for easy transfer to the installation site.

2.1. Structure Design

To keep the patient in an upright position to facilitate the rehabilitation activities, a horizontal beam that supports the weight of the patient was suggested. This beam has welded pulleys which are linked by a rope attached to a harness which holds the patient at one end and to the patient’s lifting device, on the other.
The first design proposed the use of a single cable tie. The drawback of this first design was that it did not limit the lateral movement of the patient, which can be sudden and involuntary and which may undermine the proper rehabilitation work.

The first design described required only a single horizontal beam associated with a vertical column. This unique longitudinal horizontal beam would be subjected to high stresses during lifting of the patient. The same situation of high stress would be generated on the lifting device and the only column in that design. In this sense we needed a larger section of the profiles to be used, significantly raising the cost of the device. For this reason, it was proposed to place two individual horizontal beams whereby there would be double support for the patient's weight. This enhancement allows the placement of different counterweights related to each half of the body [19]. This increases the functionality of the device with this new structure, considering that it may be useful for patients in whom the amount weight that can support by each side of the body is different. Mentioned below are some examples in which different discharges on each side of the body would be useful:

- Muscular atrophy in one member.
- Various operations on to a single member.
- Lateral or bilateral amputees.
- Hemiplegia.

The design of the device is adaptable to different rehabilitation clinic designs, where the device will be installed. The requirement is that the room has a flat supporting surface and is high enough for placement. Therefore, the beams described above are supported by columns associated with a solid base that is fixed to the ground.

Both columns should be associated with transverse beams to reinforce the structure against lateral forces generated by the patient on an involuntary basis during rehabilitation. Furthermore, this new design allowed the pulleys to be placed at different lateral positions welded to the new added beams, providing a comfortable and correct elevation (figure 1).

Longitudinal beams are welded to the columns at the end. The patient should be suspended from the front end of the longitudinal beams. This results in a bending moment determined by the product of patient weight and length of the beams. This moment can become large enough to compromise the rigidity of the structure. One solution used here is to place reinforcements in the structure (figure 2). Using a 45 degree beam between the columns and horizontal-longitudinal beams that keep the patient's weight, you get a more stable structure without affecting the ergonomics of the design.

**Figure 1.** Double column design linked by longitudinal and transverse beams.

**Figure 2.** Reinforcements above 45 degrees between side beams and columns.
As detailed above, the structure must be affixed to the ground and it is independent of walls, ceilings or walls of the room. It is necessary to build a stand that holds the various components of the structure and other mechanisms which belong to the device. This stand should be stable, stiff and ergonomic. Ultimately, the design takes into account the transfer of the patient and the mobility of the therapist around the structure.

For each column a horizontal beam was placed, which acts as a bracket attached to the floor, with reinforcements at 45 degrees on either side, which adds greater stability (figure 3).

![Base and lower reinforcements](image1)
![Winch scheme](image2)
![Photo of the winch mounted on the structure](image3)

**Figure 3.** Base and lower reinforcements.  
**Figure 4.** Winch scheme.  
**Figure 5.** Photo of the winch mounted on the structure.

Each of the base beams have two anchors, one at each end, which fix the structure to the ground and act as constraints on all axes or directions. The reinforcements help maintain the stability of the structure and counter the torque exerted at the time of raising the patient.

The length of each beam, column or reinforcement is detailed in Section 3. This will take into account the average height of patient, size of the various aids to rehabilitation such as treadmills, elliptical walkers, among others, and cost and benefit relation between stability and ergonomic design.

### 2.2. Device for patient’s elevation

At the beginning it was proposed to perform the elevation and descent of patient by means of a mechanical device. These devices are of easy manipulation and accessible price. We sought a device with the following characteristics:

- Elevation, descent and support of the patient's weight in suspension.
- Automatic brake system, both in ascent and descent.
- Safe and controlled Ascent / descent.
- Sturdiness
- Easy manipulation.
- Limited Size.
- Accessible Price.
- Easily available in the local or regional market.

Taking into consideration the aforementioned characteristics, the device of elevation that best adapts is the winch/capstan type. With this device the operator can raise a load of great magnitude exercising a small force. This device is available on the regional market in a great variety of sizes and forms.

In the winch considered ideal for this project the multiplication of force is obtained by means of a mechanism of reduction to planetary gears. It is a mechanism of long useful life by virtue of the sturdiness of all the elements. It possesses an automatic brake and that is why the operator’s attention is not necessary. With this, the accidents that happen with a winch with a manual brake disappear.
The winches were fixed to profiles welded to the columns of the structure to a comfortable height for the operator (see figure 4-5).

2.3. Mechanism of Counterweight

The design considered the aptitude to quantify the load to know with certainty how much weight is supported for the patient, knowing the load of the counterweight. A system was designed for quantification of counterweight facilitation, of easy manipulation and accessible price.

The mechanism of counterweights is based on ingots of steel of 5 (Kg) by means of which it is obtained an exact quantification of the weight reduced to the patient, satisfying this one and other mentioned characteristics.

The ingots articulate vertically by means of two cylindrical axes which allow their correct ascent and decline (figure 6).

The addition of the ingots is done by applying a pin below them, which penetrates a cylinder guide which supports the weight. This cylinder guide is joined to a rope in the top part, which is tied to the rope from the patient's restraint system by means of a device of tie (sees section 2.4). This configuration allows the addition of the counterweight needed and controlled in precise form.

The height of the structure that contains the ingots must grant the quality of dynamic unload of weight. The body's mass center changes vertically in gait. The mechanism sought has to keep the same counterweight over the patient in the course of the therapy allowing the mass center to change vertically and the load on the low members to be constant (figure 7).

The device was designed in such a way that it possesses two bodies of counterweight, offsetting the weight of the patient in right and left half. This disposition grants the possibility of training patients with asymmetric disability, who do not exercise the same distribution of load, force and neuromuscular activity in both members.

2.4. Tie of counterweights

It was sought an anchorage that possesses the aptitude to be tied to the rope from the element of subjection of the patient, from the beginning of the session and to cast off, at the end of the session a rapid and safe way. This mechanism must be small, light, safe and of easy operation. This tie remains associated to the counterweights in an uninterrupted way in the course of the therapy. The efforts that take place on the mechanism are of traction. This is due to the fact that the weight of the patient and the counterweights are opposed in direction.

After an exhaustive investigation, taking into consideration the previously mentioned characteristics, a device of tie with fist of ascension was chosen. The new element named JUMAR (see figures 8) possesses all the necessary characteristics.
2.5. Patient support

The patient's support must be at the expense of an element which redistributes the load of counterweights in a comfortable way in the body. Bearing this in mind, the chosen element was a harness which redistributes the load of the patient towards the pelvis and the trunk, diminishing the weight supported by the lower limb. The harness must be comfortable, adjustable in size and safe, besides having the fastening elements over the shoulders. The harnesses which have the previously mentioned characteristics are: the harness of complete body and the parachute harness. In the latter, the elements for harnessing the patient are more comfortable. In addition, the parachute harness possesses a good fastening of the chest giving a correct raised position. This harness is of a high cost, which is a disadvantage. The harness of complete body is composed of straps, nylon, polyester or of another type of tape, which are fastened around the body, distributing the load. Two elements of connection are necessary to allow the connection with the system of elevation by means of ropes. This type of harness is of a very low price. The chosen harness is that of complete body with lumbar fastening, which ensures a correct position. Small modifications were performed on the fastening tapes, offering comfort similar to that of the parachute harness, adapted to carry out the therapy.

3. Dimensions

Below is a list of the desirable characteristics for the determination of the different parameters of the designed device.

- Possibility of patient’s access to the device in a wheelchair.
- Dimension of supplementary devices. For example, a treadmill.
- Patient's maximum Height: 2 (m).
- Patient's maximum Weight: 150 (Kg) (hundred fifty kilograms).
- Construction of structure by means of steel ASTM A36 profiles.
- Dimensions of the ingots.
- Ergonomic Design.

3.1. Height of the structure

The height of the training supplementary devices, such as a treadmill was taken into consideration. Therefore, the dimension of the structure columns depended of the device whose work base has the
maximum height. To define that dimension, the training, vertical climber and elliptical climber were considered like standard devices in rehabilitation. The major height corresponds to the vertical climber, which is 300 (mm) high. Bearing in mind a patient's maximum height of 2 (m), columns of 2.5 (m) long were chosen, giving a safety margin of 200 (mm).

3.2. Width of the structure

The possibility of patient's access in wheelchairs, both through the front and the back of the structure was taken into account. This offers an advantage as for the orientation of the device, adapting it to the infrastructure of the available building.

A great percentage of patients with severe gait disorders cannot walk on their own, at least in the first rehabilitation phases. Having this in mind and allowing for the different possibilities of access to the device, the width of a standard wheelchair was taken as the minimum access length. This dimension is 630 (mm).

The ingots of counterweights possess a width of 130 (mm). The structures that contain them were located in the interior side of the columns. Bearing the detailed dimensions in mind, the width of the structure, or distance between columns, which gives comfortable access of the patient on wheelchair is of 1.1 (m).

3.3. Length of the structure

For the correct choice of the lengths of the structure girders, the following points were considered:

- The comfort of the patients and the professionals working in gait rehabilitation.
- The length of the supplementary devices (treadmills, climbers, elliptical good walkers) in rehabilitation.
- Material, section and the profiles length used in the structure.

The longest supplementary device is the treadmill. Its center is an ideal position for patient's work, obtaining great freedom of movement, proximity to the armrests and easy access of the therapist to the patient. The treadmill length, in average, is 1.6 (m). Bearing this in mind, the selected length dimension was 1 (m).

The base of the structure, in its front was decided with the idea of minimizing the falling moment determined by the product of the patient weight and the length from the nearest end of the base to the patient’s position. This moment has void value if the length of the previous section of the base is equal to the dimension of the longitudinal girders. Therefore, it was decided that they should be of the same length.

The base in his back part was 300 (mm).

3.4. Winch position

The correct position of winches was conceived with the idea of providing comfortable access and easy manipulation. It was chosen to place the device at elbow height, a comfortable position to realize the ascent/descent of the patient of a constant and safe way.

1.7 (m) was taken as the average height of a person in charge of manipulating the structure. Considering anthropometric tables [20] the winch was placed at 1.1 (m) high.

3.5. Dimensions of the structure which contains the counterweights

The ingots of counterweight used are 25 (mm) high. Bearing in mind the patient's maximum weight of 150 (Kg), every system of counterweights possesses 75 (Kg) in ingots. Therefore, their total height is 375 (mm).
Vertical margins of movement were given in order for the counterweights to be able to articulate while the patient does the therapy. The reason of this margin was explained in paragraph 2.3. This length is 460 (mm). This is a great margin of vertical movement, which allows the patient to move the joints of the limbs and hip. The structure that contains the counterweights has a top ceiling, which limits the movement of the ingots preventing a possible fall of the patient in case of stumbles, decompensation or imbalance of gait. The brake of the winch also avoids possible falls.

3.6. Dimensions of the reinforcements

Bearing in mind that the base must be fixed to the floor in its ends and the dimension of his back part is 400 (mm), the ends of the reinforcements were placed to 300 (mm) from the intersection node between columns and base. This reinforces the structure granting better stability. The top reinforcements were placed bearing the same criterion in mind and they were located at a similar distance.

4. Results and Discussion

The structural calculations were made using the RamAdvanse software. The calculations took into account:

- Maximum weight of patient: 150 (kg).
- Design using steel profiles (ASTM A36). Elements on the local market which has the required performance.
- Square or rectangular profiles. Through these a good final of the structure may be obtained
- Profile weight.
- Winch weight.
- The weight of strings and washers was not taken into account.
- Distance between washers.
- Structure bulwarks to the ground by 4 points.

The patient's weight is transmitted through a system of pulleys and counterweights. Each node location of the pulleys has horizontal and vertical force components which are transferred to the structure as those are welded to the it.

The separation distance of the pulleys must be the same as the distance of medial separation of the counterweights, 960 (mm), considering that these can move only vertically. Consequently, the pulleys are welded to the upper transversal beams with a distance between the pulleys of 960 (mm).

RamAdvanse software has a database of both materials and profiles. There were no features of different profiles available on the local market, so we proceeded to create and load it in the program. The obtained information satisfies the conditions of stability with a profile of 80x40 (mm).

Figure 9 shows in range of color the efforts on the designed structure.
5. Conclusions

The design criteria used for the developed device provide adaptability to almost any standard rehabilitation clinic, and even the patient’s home. The patient can access the device from the front and the back, a quality that allows that its installation is not be limited by any specific direction.

The shape and the dimensions used in the design generated wide lateral working margins, allowing the therapist to have free access to patients. This point is very relevant considering that some patients have a high degree of gait dysfunction, so therapists must simulate it through the mobilization of the lower limb segments. Moreover, the device is comfortable for both the therapist to manipulate the equipment and the patient in therapy.

The implemented device was installed at the Centro de Atención Integral y Cuidados Especiales (CAICE) from Paraná City - Entre Ríos – Argentina and it is now in operation (see details in figures 10 and 11).

Figure 9. Tensions in the structure.

Figure 10. Device installed in CAICE.

Figure 11. Patients through their therapy with the device.
The device is suitable for the rehabilitation of patients with different weights and heights, children or adults, considering the possibilities offered by the adjustable harness. The device has the ability to quantify the weight of the patient offset, allowing to decide when to increase the weight bearing in the rehabilitation process.

The prototype is ergonomic; the length and width dimensions are a few inches larger than the dimensions of treadmills, increasing the space required in a small proportion. The device was also adequate to put the treadmill at both the front and the back.

The correct sizing of the structure facilitates the use of the device with different additional equipment to help the gait rehabilitation, such as a treadmill, a stair climber and an elliptical vertical and others.

The large area of patient handling, together with the visual granted allows to study the different characteristics of gait using videography, as well as the possibility of using FES (Functional Electrical Stimulation) [21-22].

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