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MECHANICAL OPTIMIZATION DESIGN OF AN ACTIVE EXOSKELETON FOR THE KNEE DURING THE DAILY ASSISTANCE

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Annotation (Abstract Summary): *This study presents the design and development of an improved knee exoskeleton system based on the work of Andrea Mauro. The innovation introduces a compact roller mechanism to enhance adaptability and adjustability of the exoskeleton structure. The proposed system is intended for rehabilitation and assistance in daily human movements, particularly for individuals with partial mobility loss due to neurological conditions. The exoskeleton is designed to provide support equal to 30% of the maximum knee joint torque required in daily activities. The prototype enables three primary movements: walking on level ground, ascending/descending stairs, and sitting/standing from a chair. The system was modeled and analyzed using SolidWorks, demonstrating its feasibility and effectiveness for rehabilitation and assistive purposes.*

Keywords: *Exoskeleton, Knee Rehabilitation, Assistive Robotics, Biomechanics, Gait Analysis, Wearable Devices, Human Motion, CAD Design, Neurological Disorders*

INTRODUCTION

Presentation and state of the art of exoskeletons

Presentation

Many years ago, robots were used in the industrial environment to do tasks, but over the years it has been observed that they can also be useful in various areas. However, in the 70s of the centuries, it has been observed that the greater the interaction between humans and machines. Over the years some research has brought the relationship between humans and machine closer and nowadays robots are possible replace to exoskeletons applied to humans and nowadays there are three types of such equipment: active and passive exoskeletons and hybrid exoskeleton [1].

Active exoskeletons: they are powered by a source of electrical energy, which activates a suitable linear or rotary motor which in turn can be of the electric type, pneumatic or hydraulic. This engine can help the subject with various types of movement in daily life.

Passive exoskeletons: they are not powered by motors, but rather support the body with the use of various mechanical

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components, for example, spring or elastic belts.

Hybrid exoskeletons: they are a combination of the two categories listed above.

These three categories are used in different fields, from the industrial sector to soldiers and doctors. There are the following subcategories:

Industrial exoskeletons for worker support: They allow the worker to carry heavy loads and carry out repetitive and boring tasks. In general, these are active exoskeletons, and these powered by a battery that’s why workers must plan first the work and duration to be carried out with these exoskeletons.

Exoskeletons for military support: They are necessary for situations in which heavy lifting is required during combat operations. The soldier is assisted in moving these burdens by the exoskeleton in question. Notedly, nevertheless, exoskeletons are made to support weights. Soldier must recognize when it is appropriate to utilize this equipment since it is active and how long the soldier needs to perform the task because the exoskeleton is powered by a source of electrical energy.

Exoskeletons to support workers: Exoskeletons have long been introduced in some industrial settings, such as the automotive industry. Their use will become more common, in the future as they have proven to be effective in many areas. However, like any innovation technological, can bring new risks to worker health due to redistribution of non-physiological mechanical stress in other regions of the body after wearing them. This new technology also influences motor control and joint stability, altering the kinematics of the movement, for these reasons the worker must be adequately trained to its correct use. [2]

An example is the Chairless Chair robot (FIG.1) developed in 2017 by the Switzerland Noonee company. It is a passive exoskeleton to be applied to the legs that act as a wearable chair. It's enough to bend your knees for ergonomic support. The main application is companies where workers are required to stand for long periods and traditional chairs would obstruct the spaces and represent an obstacle to activity. The wearer can walk normally but decides to sit down at the appropriate time. Allows you to reduce the load, due to incorrect positions, on the legs, back, and neck. [3]

Another example is the AWN-03 (FIG.2) released in 2015 by the Japanese company Panasonic in the Asian market to support workers and older people in everyone's lives days. It facilitates lifting heavy loads by operating, thanks to the presence of sensors. That detects the movement of the worker, of the motors which generate the right torque at the level of the hips to reduce lumbar stress by 15 kg. [4]

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Figure 1 Chairless Chair [3]

Figure 2 AWN-03[4]

Exoskeletons for rehabilitation purposes: In recent years, due to workplace safety accidents and illnesses the number of injuries to functions of the limbs has significantly increased. At the same time, the average age of the population has increased worldwide (more than 11% of the American population is over 60 years old) and most have pathologies. After hospitalization, patients often regain their abilities cognitive but generally problems remain such as total or partial paralysis of the limbs, reduced ability to balance and carry out certain movements as well as difficulty in walking. Medical theory and clinical medicine have proven that the exercise of correct and scientific rehabilitation can play a really important role in the recovery and improvement of the motor function of the limb. However, due to staff shortages in nursing and high treatment costs, many patients choose to exercise at home. In this way, however, the method is not scientific and often the amount of training is not adequate, patients therefore miss the best time for recovering physical abilities. Using scientific methods and establishing a proper rehabilitation program can help patients also reduce the psychological burden linked to the impossibility of being able to move independently and therefore improve the quality of life of patients. Exoskeletons for rehabilitation are wearable robots that combine different types of technologies such as control, computing, sensors, and robots. They are designed to mimic and support the dynamics of the apparatus's skeletal muscle. Combined with traditional rehabilitation therapies they lead to better results in recovering lost functionality. The principle underlying these technologies is this of cerebral plasticity, i.e. the ability of the brain to modify its structure and characteristics functionality depending on the activity of its neurons. The repetition over time of exercises carried out with exoskeletons allows neuronal cells with greater activity to form new synapses leading to brain reorganization and recovery of certain neuromotor patterns. [5][6]

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Figure 3 Exoskeletons for rehabilitation [5]

Exoskeletons for healthcare purposes: They are used to assist in various types of movement of daily life and to lift appropriate loads. In many cases they are used by people who have irreversibly lost one, perhaps due to neurological damage part of the mobility of a limb and therefore can be useful, for healthcare purposes, so that the subject can move the limb again even if the neurological damage has been suffered it is irreversible. It is clear that even with this equipment, the subject will not be able to have 100% of the mobility he had before taking the damage. The project of this thesis will be intended specifically for a 50-year-old Italian male belonging to the 30-percentile lost part of the mobility of the right leg, to be precise the movements of the knee, due to irreversible neurological damage.

Figure 4 Robotic exoskeleton for neurorehabilitation [3]

Movement analysis Gait analysis

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Starting from Zembaty's definition [13], for which the walking cycle involves "activities and movements performed by a person walking between contact with one of the heels with the ground and its subsequent contact with the ground" or by the definition of Basmajian [14], for whom walking means "consistent locomotion in moving the body weight, focused on the center of gravity, in space, along a trajectory that requires the least energy expenditure", is defined as the path like the cyclic movement of the lower limbs that allows the body to move forward, maintaining balance and stability during support.

Instrumental gait analysis provides important support in this field clinical because it is the methodology through which it is possible to evaluate and identify the limitations of a subject's lower limbs, when only related to walking pathological. In addition to an observation analysis that allows you to evaluate, in different phases of the step, the behavior of the joints of the lower limbs, manages to obtain a complete overview also from a kinematic point of view, dynamics and muscle activation, and to be able to compare the data obtained with physiological ones. The fields of clinical application of instrumental analysis of path are numerous and are of support for the diagnosis of pathologies such as spasticity, coordination disorder, proprioception, stability assessment for people who have had a simple stroke rehabilitation after orthopedic surgery, to then move on to the application in the sports field and for the development of prosthetic and orthotic devices.

Over the years the journey has been divided and described into different phases their duration and the dependencies between the step phases and their mortgages have been determined changes induced by the changing conditions in which the movement is performed [15].

The gait cycles.

The gait cycle is the period that includes two successive supports of the same limb on the ground. From here it is clear how the purpose of the path is to allow the movement of a subject through a sequence of functions carried out by the locomotor system such as:

- Generation of a propulsion force.
- Control of the stability of the trunk despite the continuous oscillation of the postural situation
- Shock absorption with each step due to the impact of the foot with the terrain
- Conservation of energy such as minimizing the effort borne by the muscles

In the gait cycle, during advancement, a limb is used as support to allow the contralateral limb to advance to the next support, then the limbs exchange roles cyclically until reaching the situation in which both feet lie on the ground during the transfer of body weight from side to side. It is possible to divide the journey into two phases: a first phase

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of support, or stance, and a second phase of oscillation, or swing.

Support represents the entire period during which the foot remains in contact with the ground and supports the weight, begins at the moment of impact of a foot with the ground and ends at its detachment. It corresponds to approximately 60% of the gait cycle in normal walking. As far as commuting is concerned, yes refers to the time in which the foot is lifted from the ground to be able to move forward and it occupies the remaining 40% of the gait cycle in normal walking [16].

- Before proceeding with the presentation of the various phases of the step, it is important define the difference between step length (stride) and stride length (step), since often are mistakenly.
- The step length is defined as the time interval between two contacts successive of the same foot.
- The stride length is defined as the distance between the support of a foot and the support of the contralateral foot. It is usually considered the moment the heel strikes.

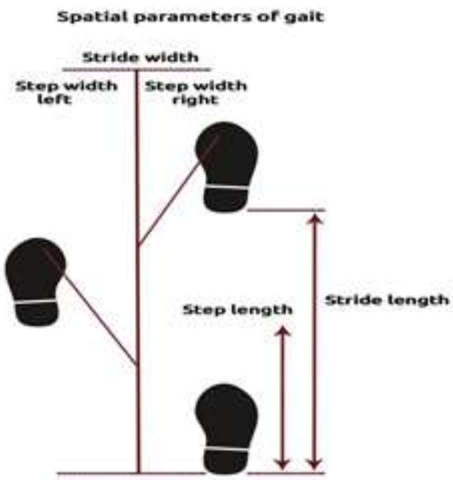

Figure 5 - step analysis [17]

The phases of the step

In 1992 J. Perry [18] identified eight sub-phases of the step, which are divided into the support phase and the swing phase, according to a certain rate of the gait cycle (Figure 6). Starting from the support phase, let's go to analyze in detail the 5 sequences that compose it:

• Initial contact (0%): it is the instant in which the heel impacts the ground, at the beginning of the cycle and represents the moment in which the body's center of gravity is located at the lowest point.

confused (Figure 5)

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• Loading (0-8%): it is the instant in which the sole of the footrests completely on the ground.

• Intermediate support (8-30%): it is the instant in which the contralateral limb is swinging leaves the ground, passes the supporting foot, and ends when it is completely resting on the ground. The center of gravity is located at the point higher.

• Terminal support (30-40%): this is the moment in which the heel lifts off the ground and continues until the other footrests on the ground. Body weight yes transfers to the forefoot. In these moments the calf begins the phase of propulsion by commanding plantar flexion of the ankle.

• Pre-pendulum (40-60%): this is the final phase of support. Represents the second period of double support in the gait cycle in which the transfer of body weight rapidly unloads the non-supporting limb no active contribution but prepares for swing request.

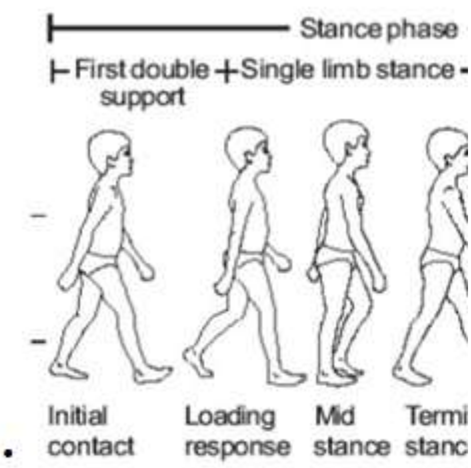

Figure 6 - angular positioning of the

As regards the oscillation phase, this is made up of three sequences:

• Initial oscillation (60-75%): this is the phase in which lifting occurs of the foot from the ground and ends when the swinging limb is parallel to the foot of support. The subject activates the hip flexors to accelerate the leg forward.

• Intermediate oscillation (75-85%): begins when the swinging limb is opposite to the supported limb and ends when the former advances and the tibia corresponding is vertical.

• Terminal pendulum (85-100%): begins with the tibia in position vertical and ends when the foot contacts the ground. It's the phase of deceleration, the muscles slow down the leg and stabilize the foot in preparation for the next support.

Presentation of anthropometric data.

The exoskeleton will be designed later and is intended for an Italian male approximately 50 years old belonging to the 95% ile Italian man for welfare purposes, it is necessary to specify the data anthropometrically, present the possible proposals intended for the subject in question, and finally the choice definitive of the exoskeleton.

The person for whom it will be intended is a 50-year-old Italian male who belongs to the 95% ile Italian man. The person lost some mobility in his right leg due to neurological damage but did

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not cause damage to the remaining anatomical parts of the leg itself, such as muscles, ligaments, cartilage, etc. This exoskeleton will therefore have to provide assistance in common life movements daily such as:

- Normal walking
- Climbing stairs
- Descending the stairs
- Getting up from a chair
- Sitting on a chair

These data refer to a 50-year-old Italian male who belongs to the 95% ile Italian man. In the following subchapters 1.1 and 1.2, the torque and angular velocity values are shown during the above-mentioned types of movement in daily life. In order to design this device, it is first necessary to analyze the three cardinal anatomical planes in order to better describe the joint movement of the human body.

Three cardinal anatomical planes, shown in figure 7, are:

- Sagittal plane
- Frontal or coronal plane
- Transverse plane.

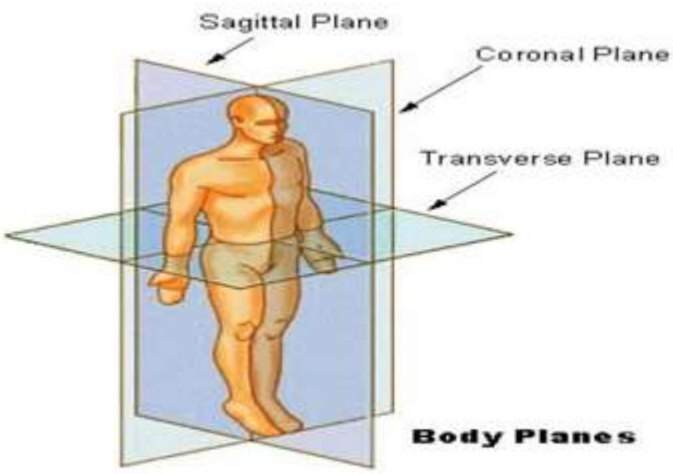

Figure 7 Cardinal anatomical planes [7]

It can easily be seen that the sagittal plane is the most used to be able to observe the profile in profile motion of the leg, but the frontal plane is also very useful to be able to better observe the joint of the knee and therefore its organs which, all together, allow the movement of the leg itself.

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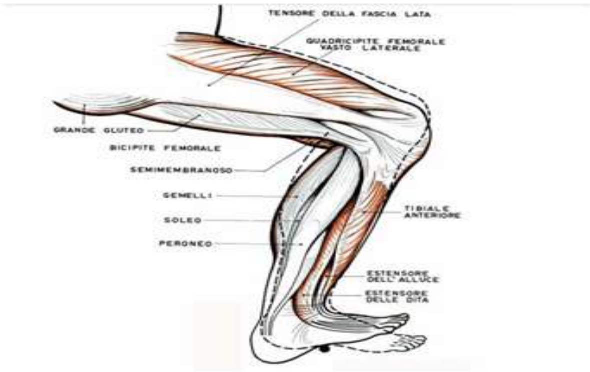

Figure 8 Anatomy of the leg seen from the sagittal plane [7]

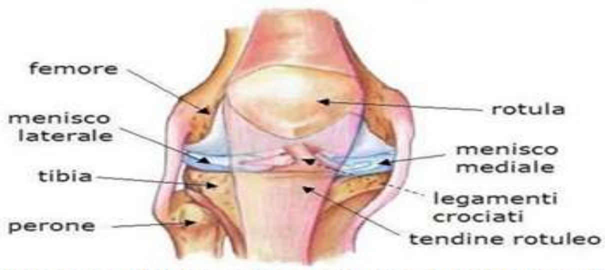

Figure 9 Anatomy of the knee seen from the frontal plane [8]

Figure 8 shows the anatomy of the leg and of course also of the knee seen from the plane sagittal. Figure 9 shows the anatomy of the knee seen from the frontal plane. Having seen and considered that the subject in question does not report damage to any of the organs involved of the leg and in particular of the knee joint shown in figures 8 and 9, can be deduced that the exoskeleton can be relatively light, constructed of textile material and with actuators electric or pneumatic in order to ensure maximum ergonomics for the majority of day. First of all, considering that the subject in question is a 50-year-old Italian male who is returning in the 95% ile Italian man it is necessary to know the relevant anthropometric data. To do this, the UNI EN ISO 7250-1 : 2010 [24] and UNI EN ISO/TR 7250- standards are very useful. 2: 2011 [25].

From these regulations it can be seen that the 50 year old Italian male belongs to the statistics grade mentioned above has the following height and body mass data:

$h = 1.834\ m$ and $m = 93\ kg$

To obtain other human anthropometric data it is necessary to use the stylized model of the human body which can be obtained by consulting the book “Physics of the human body” [11].

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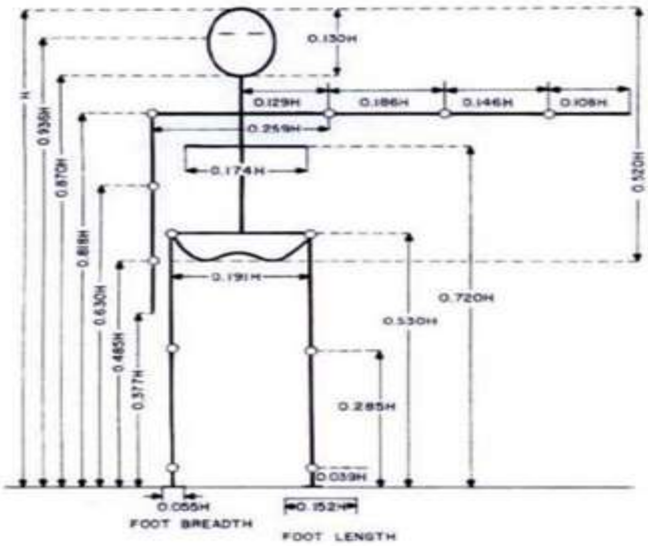

Figure 10 Stylized model of the human body [11]

From this model we can obtain the lengths of the femur and tibia shown in table 1

Femur length	= (0.53-0.285)*h =	0.449 m
Tibia length	= (0.285-0.039)*h =	0.451 m

Table 1: Femur and tibia lengths for 95% ile Italian man.

And from table 2 we can obtain the masses of the various parts of the body. This table was also obtained by referring to the "Physics of the human body" [12], by Herman Irving P

Part of the body	Part mass/total mass	Mass leaves (kg)
Hand	0.006	0.56
Forearm	0.016	1.488
Upper arm	0.028	2.604
Forearm and hand	0.022	2.048
Total arm	0.05	4.65
Foot	0.0145	1.3485
Calf	0.0465	4.3245
Thigh	0.1	9.3
Foot and calf	0.061	5.673
Total leg	0.161	14.973
Head and neck	0.081	7.533
Torso	0.497	46.221

Table 2: Masses of the various parts of the body of a 95% ile Italian man

If the following data is added, the value of the total mass of the organism must be obtained subject in question, i.e. 93 kg. Therefore:

$$\text{Total leg} * 2 + \text{Total arm} * 2 + \text{Torso} + \text{Head and neck} = 14.973 * 2 + 4.650 * 2 + 46.221 + 7.533 = 93\ kg$$

From the result obtained it can be deduced what calculations of the various parts of the body obtained in the table. For the design of the exoskeleton, the length and mass values of leg will be especially useful total, thigh, calf and foot. As regards the actuation, both electric and pneumatic, it will be very important to know the value of the torque

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that the motor will have to withstand and the angular velocity of the tibia with respect to the femur (from 0° to 100° during flexion and vice versa for extension).

Conclusions and future developments

1. Conclusions

In this thesis we continued previous Andrea Mauro's thesis, and we completed design of an exoskeleton to be assembled on the right leg. This work was done for a 50-year-old Italian male belonging to the 95% ile Italian man as aid for various types of movement in daily life. To carry out this work, research was first carried out on the state-of-the-art exoskeletons applied to the leg to improve its mobility and bearable torque and was subsequently carried out extensive research on the studies already present in the Andrea Mauro's thesis literature to understand the values of couples were necessary, such as force and pressure values. Always based on existing studies various proposals have been made in the literature, of which only one has been taken into account consideration, and from it the entire project and elaboration of this thesis was developed. The other proposals were not set aside but were left as an indication of the future.

Thanks to Andrea Mauro's studies it was possible to obtain good sizing and an optimal result both in terms of weight force and size on the frontal and sagittal planes. Various considerations and analyses were also made on the impact that a change would have on some sizing parameters.

Finally, the 3D model was simulated and developed using the CAD software "Solidworks".

2. Future developments

Our research certainly focused on analysis and studied that certify the safety of the use of aluminum materials with pressures so that they will can be helpful for other exoskeleton creation and that will also aid in the various types of leg movement being for movements. However, in future years it is expected that, if this were to be achieved, the application of such exoskeletons would certainly be helpful for healthcare purposes and certainly industrial environments.

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