Design and virtual model of an exoskeleton for lower limb rehabilitation

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Abstract. In this paper the design and the virtual model of an exoskeleton for human lower limb rehabilitation is developed. The proposed exoskeleton is anthropomorphic, low cost and easy to adapt on the human subject. The design aspect concerns the exoskeleton mechatronic structure achieved in Solid Works virtual environment. In order to realize the multibody model, the virtual spatial model of a human mannequin developed in SolidWorks was transferred to the ADAMS database. The movement laws experimentally collected are introduced in each of the 6 rotational joints of the both lower limbs. Simulation of the mannequin walking is performed.

1. Introduction

More and more studies are dealing with the analysis of normal and pathological human gait in order to design bioinspired robotic structures, as virtual design based on the specific tools of computer-aided-design, or as physical prototypes used in the industry in the form of humanoid robots and collaborative robots [1-13], in biomechanics or clinical medicine as orthotic systems, [13-17] exoskeletons [18-33] and medical robots [32-36] used in the field of rehabilitation. In rehabilitation therapy, the main goal is to sustain the mobility functional of disabled patients, this procedure requiring a repetitive motion performed by the patient. In the last time, the rehabilitation techniques use more and more mechanical systems (exoskeletons and robots) to assist the lower limbs in their movements’ rehabilitation and many review studies which evaluate the technology progress and future directions in rehabilitation were published in recent years [11, 19, 20]. Among the benefits of robotic rehabilitation are: reducing dependence on clinical staff; providing adequate rehabilitation movements and adjusting the level of treatment according to patient requirements; allowing control of joint movement, helping ensure controlled repetitive preparation at a reasonable cost [25]. Exoskeletons for industrial application are presented in [3-6, 8-11], powered exoskeletons in post-stroke rehabilitation are studied in [24]. Simple recovery devices and multi-joint exoskeletons are described by [21-22, 25-30], where most of the devices are based on the principle of predefined gait trajectory control. This principle is based on the implementation in the device control system of a data package acquired from a healthy person and the exoskeleton replicates the desired joint trajectory. The aspect of control systems of active exoskeletons is studied in [9-12, 14], while aspects of exoskeleton design, path planning, modelling and simulation, experimental tests are studied by [34-37]. In this paper, the design and virtual model of an anthropomorphic exoskeleton low cost and easy to adapt on the human subject used for lower limb rehabilitation will be presented. In order to realize the multibody model, the virtual spatial model of a human mannequin developed in SolidWorks was transferred to the ADAMS database. The movement laws
experimentally collected are introduced in each of the 6 rotational joints of the both lower limbs. Simulation of the mannequin walking is performed.

2. Experimental study
The human experimental study is performed using the Biometrics Ltd [38]. Data Acquisition system based on wearable electrogoniometers. The wearable Biometrics system allows capturing information during human gait and analysing biomechanical data outside the laboratory [22, 23, 39]. For data acquisition, were used three 8-channels DataLOG devices, at a frequency of 500 Hz, two for connecting the electrogoniometers and one device used for the six plate forces used for collecting the data of ground reaction forces. In Figure 1 the subject with mounted electrogoniometers, force plates and DataLog device are shown. Using Biometrics system the experimental measurements was performed for five trials of 20 consecutive walking cycles of a male subject. The subject was pain-free and had no evidence or known history of motor and skeletal disorders or record of surgery to the lower limbs. The anthropometric data of the human subject are shown in table 1.

| Mass [kg] | Height [cm] | Length of the leg [cm] | Length of hip-knee segment [cm] | Length of knee-ankle segment [cm] |
|-----------|-------------|------------------------|---------------------------------|----------------------------------|
| 70        | 176         | 84                     | 43                              | 41                               |

The experimental data were acquired for all six joints lower limbs and for overground walking cycles on six force platforms. In figure 2 are presented the diagrams of flexion-extension angles of the ankle, knee and hip, collected for both legs (right and left) sing the acquisition data system and in figure 3 the diagrams of Ground Reactions Forces corresponding to the trial 1 are presented.

Figure 1. The block diagram of the data acquisition process
Figure 2. Diagrams of consecutive cycles of variation of flexion-extension angles in sagittal plane and rotation in the front plane represented by the software based on experimental data collected for both hips, both knees and both ankles.

Figure 3. The experimental Ground Reactions Forces variations on the six force platforms.

3. The virtual model of the exoskeleton

The development of the new device has started from the idea of reproducing the movement of the lower limbs as close as possible to the human one and the possibility of varying the flexion-extension angles for each joint. The proposed exoskeleton aims to recover and improve walking in people with lower limb disorders, like knee osteoarthritis, or hip osteoarthritis. Therefore, the proposed device can be used in rehabilitation therapy and can be adapted to a recovery of the joint motion of both lower limbs, as well as of a single lower limb. The virtual model of the exoskeleton is shown in Figure 4.a.

The solution presented is one with low energy consumption, for the actuation of the whole device, a single rotary motor being used which drives using chain transmission. The device features 8 elements and 10 rotation spindles in its structure. The metal frame is designed to meet several features: simple construction; modularity; enhanced ergonomics; safety.

Figure 4. a) The virtual model of the exoskeleton b) The virtual model of the lower limb of the exoskeleton, c) detail A-power transmission system.
The exoskeleton was designed in a similar way to the human lower limbs, both in terms of the mechanical model and the drive system, as well as in terms of size, shape and overall appearance. The dimensional and mass characteristics of the lower limbs have been studied for the purpose of imposing them as input data in the design of the exoskeleton. The virtual model of the inferior limb of the exoskeleton is shown in figure 4.b.

The elements in figure 4.c. have the following meanings: 10 - bar type element corresponding to the femur; 11 - bar type element corresponding to the tibia; 12 - bar type element that helps to achieve the flexion-extension angle of the knee; 13 - bar type element that helps to achieve the flexion-extension angle of the ankle; 14 - bar type element for the foot; 15 and 16 - bar type elements by which the amplitude of the flexion-extension angle of the three joints is adjusted; 17 - a chain toothed wheel that converts the rotation motion of the electric motor into a pivotal motion of the elements 10 and 13; 18, 19 and 20 - chain gears that are part of the power transmission system; 21 and 22 - chains through which power is transmitted; 23 - Electric engine.

The entire movement of the exoskeleton is generated by a single electric motor. The transmission of power from the engine to both lower limbs of the exoskeleton is achieved by mechanical transmission composed by the gears 18, 19 and 20 and the chains 21 and 22.

The principle of the hip joint functioning movement is inspired by human hip movement, the device being designed to provide a flexion-extension movement that meets the experimentally measured parameters on subjects. The main component of the hip joint is the element 10 similar to the human femur. The actuator rotates the chain gear 17 fixed on the frame in joint A and transfer the motion to link 16 being connected by joint B to chain gear, and by joint C to femur segment. The femur segment represented by link 10 and is fixed on frame by joint D, takes over the movement from link 16 by joint C and converted it into a pendular movement which represent the flexion-extension movement.

In figure 5.a. the virtual model of the hip joint of the exoskeleton; 5.b. the principle of the hip joint functioning is presented.

![Figure 5](image)

**Figure 5.** a) The virtual model of the hip joint of exoskeleton; b) The principle of hip joint functioning

The movement of the exoskeleton knee joint mechanism is designed to perform a flexion-extension movement that meets experimentally measured parameters on subjects. The knee joint is composed by two main elements: link 10 (femur) and link 11 (tibia) fixed by joint F and a secondary element: link 12 fixed with link 11 by joint H. The chain gear transfer the motion to link 15 by joint A. The secondary element (link 12) take over the motion from link 15 by joint E and transfer it to link 11 by joint H. In figure 6 are presented the a) The principle of knee joint operation; b) Virtual knee joint model; c) Movement system to the knee joint. The movement of the exoskeleton ankle joint is the result of the action of two main elements: the link 11 and the element 14 representing the foot, as well as a secondary element, 13. The movement of the ankle joint, unlike the other two joints, is not driven by the electric motor, but is the result of the combination of the movements of the three elements mentioned above, 11, 13 and 14. The flexion-extension angle of the ankle joint is formed by the movement of the knee joint to which the movement of the element 13 is added. In figure 7 is presented the principle of the knee joint operation and Ankle joint operation principle.
4. Virtual Model of the Mannequin

The virtual model of the mannequin developed in SolidWorks, presented in [22], and used in these simulations respects the kinematic structure and mass properties of the locomotor system. The virtual model of the elaborated mannequin respects the kinematic structure and mass properties of the locomotor system. The virtual model of the human mannequin was developed in SolidWorks using the anthropometric data of the human subjects in table 1. The mannequin data obtained in SolidWorks can be easily modified in case of research done on different human subjects due to the parameterized design. In figure 8 the virtual assembly of the mannequin made up of 13 component parts, connected by kinematic rotational couplings is presented.
In order to realize the multibody model, the virtual spatial model of the mannequin developed in SolidWorks was transferred to the ADAMS database. The mannequin was modelled so that the lower limbs consist of three segments: femur, tibia and foot and three joints: the hip, knee and ankle joint. The three joints were simplified in the form of rotational joints to allow the flexion-extension movement to be reproduced. The definition of the three kinematic joints corresponding to the lower right limb is presented in figures 9-11.

**Figure 9.** Definition of the kinematic joint corresponding to the hip

**Figure 10.** Definition of the kinematic joint corresponding to the knee

**Figure 11.** Definition of the kinematic joint corresponding to the ankle

The next step of the modelling was to introduce the movement laws experimentally collected in each of the 6 rotational joints of the lower right and left limbs. The experimental data, in tabular form, were introduced in ADAMS and were interpolated as SPLINE functions, using the Akima method. In figures 12-14 the graphs of variation of the Spline functions of the right hip, knee and ankle joints are presented.
Similarly, the experimental data were entered for the three joints of the lower left limb and the corresponding spline functions were determined.

An important aspect of the construction of the multibody model is the definition of the contact model between the sole and the floor. The virtual simulation environment ADAMS has the possibility
to perform calculations on a rigid-elastic model, in which the contact bodies are considered rigid and the contact surfaces are considered deformable. Contact modelling is based on the impact method. In ADAMS it is possible to use the impact method for defining the contact, by introducing a cubic function of the form [22]:

\[ F(x, v) = kx + \left\{ c \left( \frac{x}{d} \right)^3 \right\} v \]

where:
- \( k \) is a linear constant, (the model of a linear arc);
- \( c \) is the damping coefficient;
- \( d \) is the penetration depth.

The damping force is zero when the depth of penetration of two bodies is zero and reaches the maximum value when the depth of penetration is reached \( d \) [40, 41]. The approximate values of the contact coefficients introduced in ADAMS, by the impact method, are: \( k = 46.58 \) N/mm; \( c = 97.19 \) N/mm/sec and \( d = 16 \) mm [22]. Taking into account the above considerations, the contact between the sole and the ground was defined according to figure 15.

The solution of the dynamic model was realized by using the WSTIFF solver and the SI2 integration algorithm. The results obtained by the ADAMS simulation consist of graphical results representing the trajectories of the joints. The trajectories performed by the centres of the three joints obtained from the numerical simulations in ADAMS are shown in figures 16-17. The walking stages performed by the mannequin during the simulation are presented in figure 16 b.

**Figure 15.** Insert contact parameters

**Figure 16.** a) The trajectories of the centres of the three joints of the mannequin; b) Successive positions of the manikin on the ground
5. Conclusions
The design, the virtual model and the constructive and functional principles of an exoskeleton for human lower limb rehabilitation are presented. The proposed exoskeleton is anthropomorphic, low cost and easy to adapt on the human subject. The design and the exoskeleton mechatronic structure is realized in Solid Works virtual environment. The virtual spatial model of a human mannequin developed in SolidWorks was transferred to the ADAMS database in order to develop the multi-body robotic structure. The movement laws experimentally collected by using Biometrics system are introduced as tabular data in each of the 6 rotational joints of the both lower limbs; two hips, two knees and two ankles. Simulation of the mannequin walking is performed. A future work we intend to continue the numerical simulations in order to obtain the ground reaction forces and the reaction forces in every joint as well as the optimisation of the mechatronic structure of the exoskeleton.

6. References
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