Actuation System Selection of ALICE Exoskeleton Robot Based on Dynamic Simulation

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***Abstract*—In this paper the actuation system selection for ALICE exoskeleton robot based on the torque obtained from gait analysis of healthy subject and subjects with multiple sclerosis is presented. The exoskeleton robot was designed in Autodesk Inventor considering the weight-body of an average person, then the model is exported to Simscape Multibody and the signals are set from data obtained with commercial medical equipment, CODA™ Motion Analysis System, at the Physiotherapy Clinic of the ONCE Foundation. Finally, considering the nominal and peak the torque obtained, it is proposed the electrical motors, reducers and control board from manufacturer's catalogues.**

***Index Terms*—Actuation System, CODAmotion, Dynamics, Exoskeleton, Rehabilitation Robotics, Torque**

I. Introduction

An exoskeleton in an electromechanical device that is used for rehabilitation tasks, increase of force, or assistance to locomotion [1], [2], [3], typically an exoskeleton consists of a mechanical system, an electronic system made up of sensors which allow to determine not only the positions of the joints or joints but also assess forces, and in some cases electromyography sensors are also included to measure movement intentions. In addition, there is an actuation system which usually consists of motors and an electronic control system.

In the case of exoskeletons intended to improve physical skills, is intended to provide the user with greater physical capacity, in the case of assistance with locomotion, the person who uses it generally has total paralysis and the exoskeleton helps to generate a normal gait, in the case of rehabilitation, the exoskeleton must be able to provide the necessary torques to generate a normal gait for rehabilitation purposes, in this sense the torques generated by each person become disturbance torques and the system must be capable of adapting the control system by imparting the necessary torques to achieve normal walking, thus, it is important to have a suitable selection of the actuation system when designing this type of mechanism.

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Therefore, one of the most important stages in the design of robots is the selection of the actuators, since they must be capable of generating the torques required for the proper function of the exoskeleton [4]. There are several methods to select the actuators based on the Dynamic Analysis, the classic methods consist of determining the equations of the inverse dynamics from the mass, inertia and velocities of its elements, among the methods to calculate the dynamics and therefore the torque we have: Newton-Euler's method, Lagrange-Euler's formualation, and D'Alembert's generalized equations [5], [6]. Although the methods appear to be systematic, there is always great difficulty and mathematical complexity in the calculation.

This work presents the actuation system selection of ALICE exoskeleton robot, the ALICE project consists of a low-cost lower limb exoskeleton which is indented to provide high performance of rehabilitation processes, ALICE has an intelligent control with the ability to adapt to the rehabilitation process according to the evolution of each patient [7], which allows covering all the phases of the process at the same time, offering real-time data on the current state of the injury. On the other hand, it includes a novel control system in which the biomechanical modeling of the subject is included.

For deal with the dynamics and torque evaluation, an alternative method based on dynamic simulation is presented, thus, the CAD is first designed in Autodesk Inventor and then exported to Simscape Multibody™(formerly SimMechanics ™), thus, an equivalent plant is generated.

Moreover, the joints angles for normal or pathological gaits could introduced to the plant in order to obtain forces and torques, as the case may be. For this work, gait data were taken from healthy subjects and subjects with multiple sclerosis at the rehabilitation clinic at ONCE foundation in Madrid, Spain. These joint angle values are entered into the plant in SimMechanics ™to evaluate the torques generated in each joint, then, with the torques generated in each joint, we can identify the most suitable actuators, reducer and control board from manufacturers catalogs.

This work is organized as follows, first the ALICE project is presented, then the methodology for the dynamic analysis is shown, next, the simulations results are analyzed, and then the actuator selection is discussed, finally, the discussion and some conclusions are presented.

II. ALICE Exoskeleton

The main objective of the ALICE project is to provide physical therapists with a tool that helps in the rehabilitation process and allows them to reduce the workload. ALICE is a lower limb rehabilitation exoskeleton, consists of 3 links (pelvis, femur and tibia) and includes 3 electric actuators. The first version of ALICE includes 4 degrees of freedom (GDL), 3 active (hip flexion / extension, hip abduction / adduction, and knee flexion / extension) and a passive (dorsal / plantar flexion of the ankle) [8].

The exoskeleton is adjustable for patients with femur and tibia lengths between 35 cm to 50 cm and pelvic width from 29 cm to 40 cm, [9]. ALICE is designed to assist in the rehabilitation of gait for patients who have suffered a locomotor injury as a result of neurological or muscular disorders. The intended use of ALICE includes patients with conditions such as stroke, multiple sclerosis, Parkinson's disease, neurological disorders, musculoskeletal injury, or cerebral palsy.

ALICE is composed of an adaptable base to the pelvis and 2 adjustable elements that adapt to the femur and tibia respectively, as shown in Fig.1.

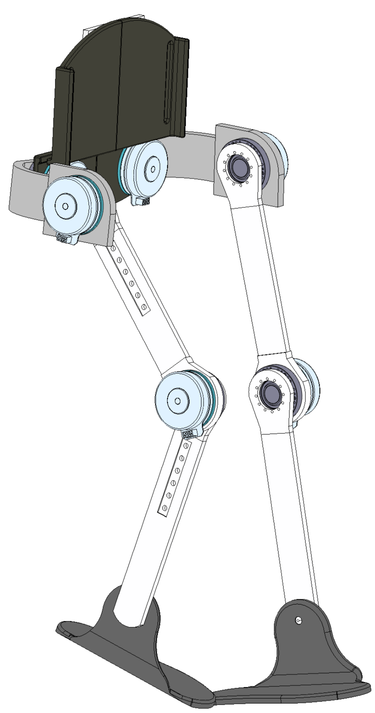

Fig. 1. Exoskeleton Rehabilitation Robot, ALICE

The robot has 3 joints for each limb, allowing 3 active and 1 passive degrees of freedom. The first active joint corresponds to hip abduction / adduction, the second active joint to hip flexion / extension, and the third active joint corresponds to knee flexion / extension. Finally, the passive degree of freedom corresponds to the ankle, allowing dorsal and plantar flexion.

The range of motion of each joint is restricted to the values found in the literature, [10], [11], [12] and are shown in Table I.

TABLE I
Joints and Range of Motion (ROM) of ALICE.

Joint	Action	ROM
Hip	Extension/Flexion	$-30°/120°$
	Abducction/Aducction	$-50°/30°$
Knee	Flexion/Extension	$-120°/0°$
Ankle	Flexion Plantar/Dorsal	$-40°/30°$

III. Dynamic Simulation

The dynamic analysis of a robot aims to know the relationship between the movement of the robot and the forces involved, this relationship is known as the dynamic model of the robot and consist of a set of mathematical equations that describe the dynamical behavior of the mechanism. Thus, the dynamic model is a mathematical relationship between the location of the robot and its derivatives (velocity and acceleration); the forces and torques applied to the joints (or in the end effector); and the dimensional parameters of the robot such length, mass, and inertia of its elements [13], [14], [15].

The robot's dynamic model is an important tool not only for the mechanical design of the robot (sizing of links, bearings, and actuators) or computer simulations to predict its behavior but also for developing suitable control strategies. The dynamics of a robot can be classified in direct dynamics and inverse dynamics. The direct dynamic problem, deal with the resulting motion in the mechanism when some torques or forces are applied. The inverse dynamics deals with the joint torques or force needed to produce a desired motion (trajectory) of the robot. For control algorithms, the inverse dynamics play a key role since takes part in the control architecture allowing us to know the joint torques evolution.

In this paper we present a straightforward approach to solve the inverse dynamics and then to determine the joint's torque. The method proposed start with the design of the mechanism in order to obtain the nominal and peak values of the torques in each actuator, the robotic device is simulated in a software environment implementing the trajectories defined.

Thus, ALICE's CAD model was exported to Simulink®, Simscape Multibody™ from the Autodesk Inventor Design.

On the other hand, in order to select the actuators, patient's weight was added to the CAD model (considering a maximum weight of 135 kg) and then exported to Simulink®. The equivalent Simulink® model allows evaluating the needed torques for a pure movement and integrating all the MATLAB® and Simulink® features. Fig. 2 depicts the equivalent Simulink® model.

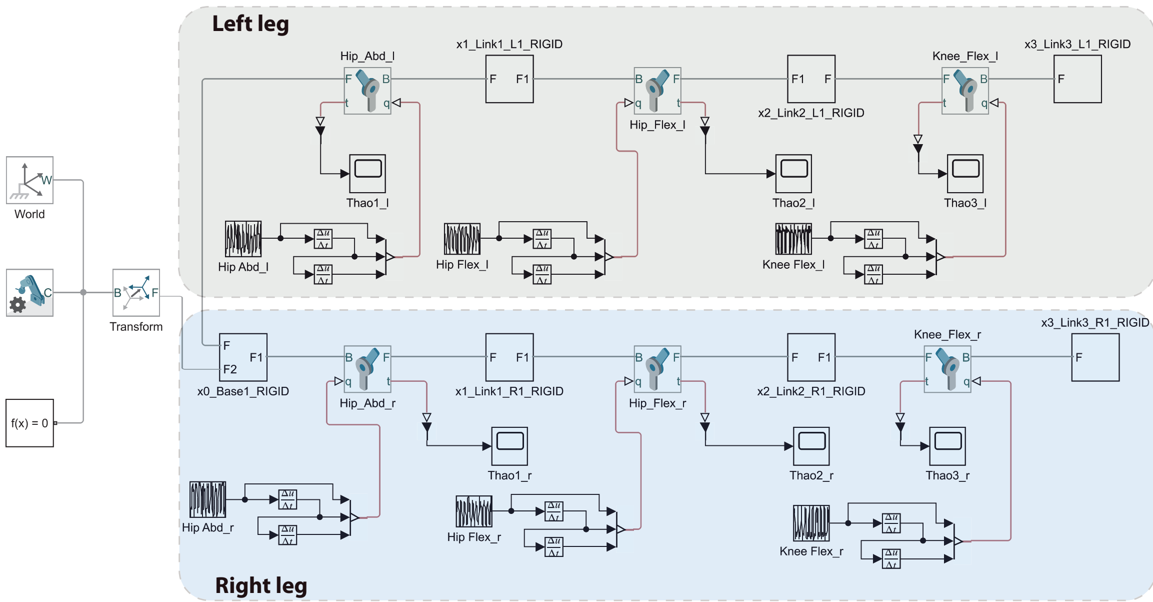

Fig. 2. ALICE, Simulink®, Simscape Multibody™ equivalent model.

Once the model was exported, activation signals for a normal and pathological gait were set as reference joint's angles, and the required torque was determined. The gait signals were obtained at the Physiotherapy clinic at the ONCE Foundation in Madrid using CODA motion system [16].

The dimensions and physical properties of ALICE [7] are shown in Table II, while inertia matrices are shown in (1).

TABLE II
ALICE LENGTH AND MASS VALUES.

Parameter	value
l_1	0.115 m
l_2	0.160 m
l_3	0.400 m
l_4	0.400 m
m_1	1.18 kg
m_2	13.228 kg
m_3	5.594 kg

$$
\begin{aligned}
I_1 &= \begin{bmatrix} 0.004977351 & 0 & 0 \\ 0 & 0.004835199 & 0 \\ 0 & 0 & 0.001191692 \end{bmatrix} \\
I_2 &= \begin{bmatrix} 0.009337758 & 0 & 0 \\ 0 & 0.166430481 & 0 \\ 0 & 0 & 0.169652773 \end{bmatrix} \\
I_3 &= \begin{bmatrix} 0.019400497 & 0 & 0 \\ 0 & 0.135966856 & 0 \\ 0 & 0 & 0.146655675 \end{bmatrix}
\end{aligned} \tag{1}
$$

where ALICE length and joint rotation axis are shown in Fig. 8.

IV. SIMULATION RESULTS

Once the model was exported, activation signals for normal gait and pathological gait were set as reference joint's angles,

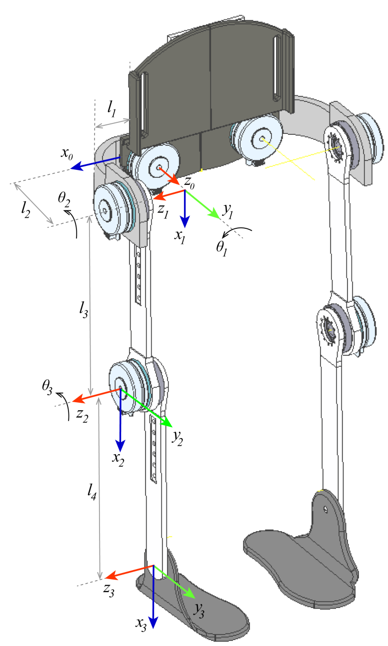

Fig. 3. ALICE length links and joint axes rotation [7].

and the required torque was determined. Fig. 4 shows the joint's angles of reference for normal subject whereas Fig. 5 shows the joint's angles of reference for pathological gait.

On the other hand, Fig. 6 and 7 depict the torque evolution for normal and pathological gait. From the results we have an average and peak torque required for hip flexion/extension, hip abduction/adduction, and knee flexion/extension for normal gait of 38 N.m (85 N.m), 28 N.m (84 N.m), and 10 N.m (40 N.m), respectively. Moreover, the flexion/extension, hip abduction/adduction, and knee flexion/extension torque required

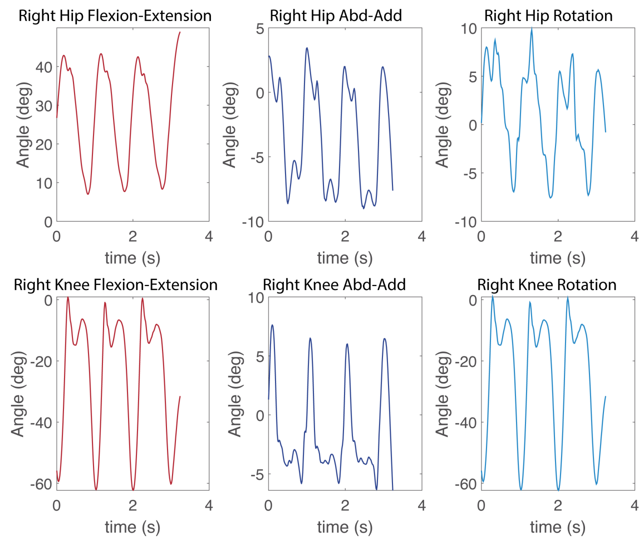

Fig. 4. Reference joint's angles for normal gait .

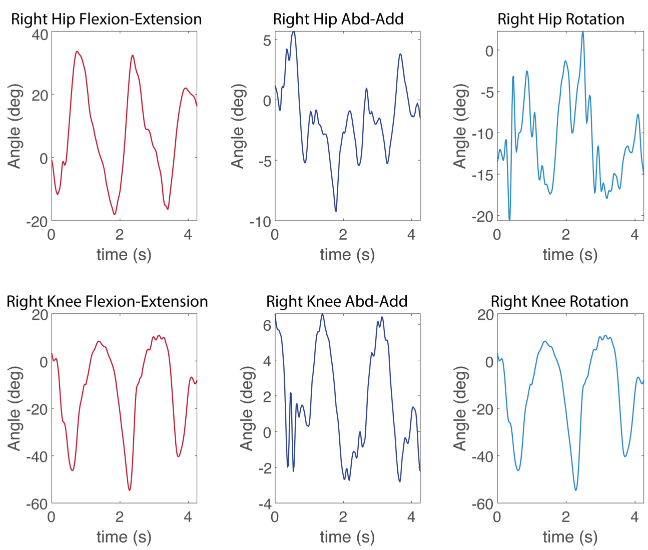

Fig. 5. Reference joint's angles for pathological gait .

for pathological gait were around 35 N.m (58 N.m), 20 N.m (75 N.m), and 8 N.m (17 N.m) respectively.

V. Actuator Selection

In order to select the actuation system, we will take into account the results of the torques selected in the previous section and a safety factor of 20% will be added, thus, the average torque values considered are shown on Table III

Based on the values shown in table III, the selection of the actuators and control board is performed from Maxon motors catalog, while for the reducers, the Harmonic Drive catalog. Furthermore, considering that the final exoskeleton should be compact, light weight and comfortable to the user, the recommended actuation system is summarized in the Table IV.

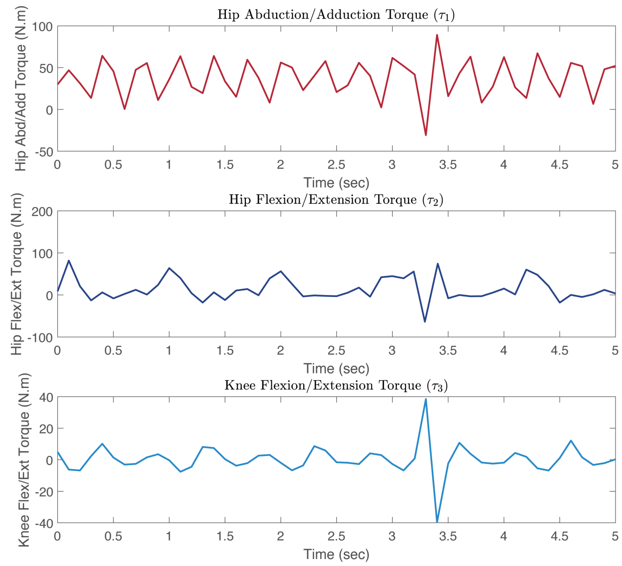

Fig. 6. Joint's torque predicted for normal gait.

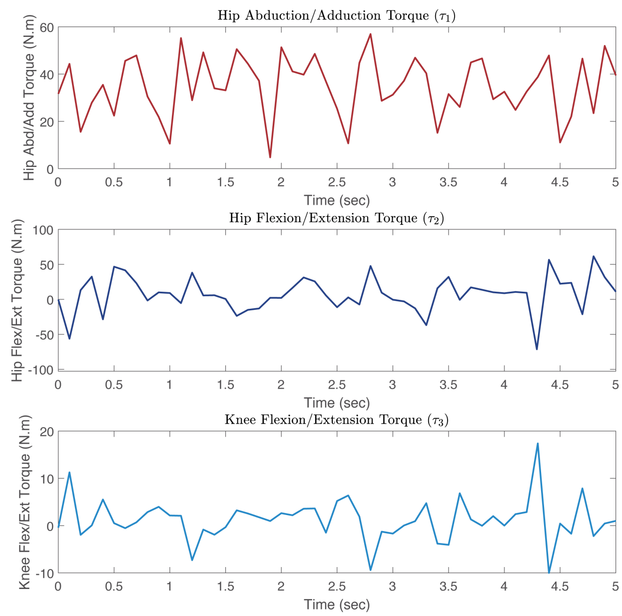

Fig. 7. Joint's torque predicted for pathological gait .

TABLE III
Nominal and Peak Joint's Torque

	Normal Gait (N.m)		Pathological Gait (N.m)	
Joint	Nominal	Peak	Nominal	Peak
J1	45.6	102	42	69.6
J2	33.6	100.8	24	90
J3	12	48	9.6	20.4

The actuation system components selected are shown in Fig. 8, 9, and 10.

TABLE IV
ACTUATION SYSTEM SELECTION

Joint	Motor	Reductor	Board	Voltage (V)	Torque (N.m)	Peak Torque (N.m)	Gear Box	Speed (RPM)
J1	EC Flat 90	HD CSG 14 2UH	EPOS2 70/10	24	14	58	80	21.68
J2	EC Flat 90	HD CSG 17 2UH	EPOS2 70/10	24	51	109	100	27.1
J3	EC Flat 90	HD CSG 17 2UH	EPOS2 70/10	24	51	109	100	27.1

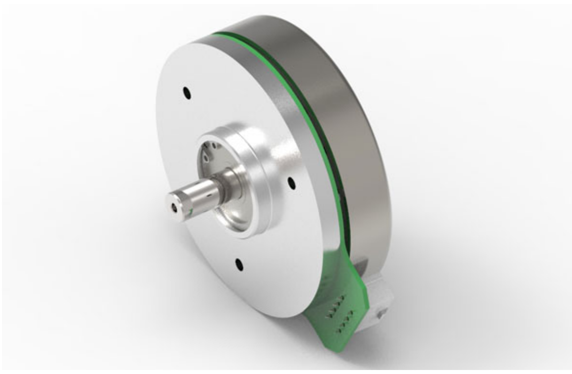

Fig. 8. EC Flat 90 from Maxon Motors.

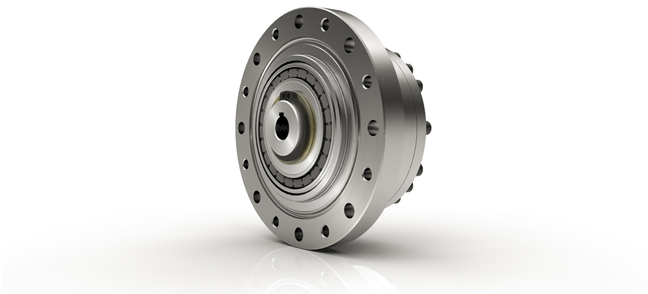

Fig. 9. Harmonic Drive reductor CGS 17 2UH.

Fig. 10. EPOS2 70/10 control board from Maxon Motors.

VI. DISCUSSION AND CONCLUSIONS

In this work, the selection of the actuation system of a rehabilitation exoskeleton based on the torques obtained from a dynamic simulation has been presented. Reference angles for the joints have been considered, and have been taken at Physiotherapy Clinic of the ONCE Foundation in Madrid, for both, a healthy subject and a multiple subject. In addition, it has also been considered a safety factor for motor selection.

The result obtained has been a EC Flat 90 series motor in combination with an Harmonic Drive reducer and an EPOS2 control board, for which it has also been taken into account that the device must be light and comfortable. The control board was chosen based on the fact that allows us to develop control algorithms in C++ more as well as LabVIEW through the CompactRIO libraries.

On the other hand, the voltage supply must comply with the regulations specified for electro medical devices and risk management of medical equipment, such as ISO14971, and the corresponding technical standards of the harmonized IEC / ISO series such as IEC 60601-1, which is specific electrical safety of medical equipment.

Finally, our project is in the process of validating components/subsystems and performing laboratory tests and simulations in a real environment. ALICE has an average level of technological maturity (TRL) (level of technological preparation, NASA) of 5. As a future work authors will begin to assembly the device and deal with advanced control strategies.

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