Child Lower Limb Exoskeleton: Sizing and Modeling

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Abstract—This paper[6], presents the sizing methodology of direct drive actuator for a new lower limb exoskeleton to operate effectively. The main objective of the latter exoskeleton is the mobility aid of the paralyzed children in order to move their lower limb again and perform a gait motion. the applied torques on the actuator are calculated by two methods based on the bio-mechanical data from literature and by taking in consideration the quasi-static loads applied in the worst case situation by the wearer. Also, a verification of the results is done using a virtual model on Matlab-Simulink®.

Index Terms— Exoskeleton; Paraplegia; Spinal Cord Injury; Mechatronics; Servo Actuators; Orthotics; Lower Extremity.

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1 INTRODUCTION

Across the entire world, 68 million people and more are suffering from paraplegia because of several reasons (spinal cord injury, stroke, brain disorders, genetic factors…etc). The ordinary solution to help on mobility is the use of traditional wheel chair. The latter solution may solves the problem partially, but their freedom is still limited. On the other hand, there are some diseases and possible distortions arise due to sit on a wheelchair such as back and legs ulcers, muscular atrophy, Osteoarthritis … etc.

And also some disorders and psychological problems appear because of the sense of helplessness and loss of mobility, balance and carry out daily activities like other people. But those people who are paralyzed, they have the right to exercise their normal lives, though the walk and sit down and go up the stairs ... etc.

Using exoskeleton, the possibility to move the upper/lower limbs is recovered, so the patients can sit down, stand up, walk, climb and descend stairs again[1,2,3,4]. But the majority of the existing exoskeletons are not dedicated to fit the children needs. Where children's physical and psychological needs and requirements are different from the needs of adults and the elderly. Because the shape, size and suppleness of their bodies plays an important role in the study and design of the exoskeleton devices. Therefore it maybe difficult for them to wear complicated devices.Also taking into account the risks caused by the non regular movement which can cause an injury while using such powerful exoskeleton.

Hence, exoskeletons tend to be an effective solution to the children patients suffering from SCI, or other disorders…etc, but sizing on all the levels of this solution is an open question since it depends on several conditions such as the inertial parameters (the weight, size, length), the kinematic and dynamic parameters (the walking speed, wearer weight, type of the activity to do, level of performance...etc), and other medical constraints (the type of the disorder or the injury... etc).

The paper is organized as follows: In section II, a state of the art treats the current lower limb exoskeletons. In section III, a bio-mechanical study is shown to understand the human lower limb motion and gait analysis. Then, in section IV the methodology of actuator sizing is presented. In section V the results are illustrated and summed up. Exoskelton modellingis shown in section VI. Finally, the conclusion of the work done is presented.

2 STATE OF THE ART

Several functional rehabilitation and compensation exoskeletons were presented since some decads. The most important of these devices are the Rewalk walking assitstance exoskeleton, designed by Argo Medical Technologies [5].The Hybrid Assistive Leg (HAL), developed by Cybernics Laboratory of the University of Tsukuba in Japan [6]. Indego developed in the University of Vanderbilt (Tennessee, United States) [7]. The EKSO developed by EKSO Bionics [8]. The Berkeley Lower Extremity Exoskeleton (BLEEX)[9], developed by the University of Berkeley in the USA. The phoenix exoskeleton developed by SuitX[10].

Rewalk gives the opportunity for patients which are having disabilities on their lower limbs to stand, sit, walk, and ascend /descend stairs. The two actuated joints are the hip and knee but they are active only in the sagittal plane of the human body, the actuation is achieved by a seies of high torque actuators, so the ankle joint is not actuated but it is having a limited range of motion achieved spring for dorsi-flexion degree of freedom. It can walk with a linear speed of 2.2 km/hour [11]. The wearer uses crutches to address stability during walking. Rewalk's sensor system is located on the upper body and on a hand watch, so it measures the device inclination to recognize the wearer's intention to generate motion or to stand up or sit down.

HAL is a full body exoskeleton, it is considered as a walk-

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ing aid system and being used for people with walking disorders. The lower limb degrees of freedom (hip, knee, and ankle) are actuated only in the sagittal plane, while the upper body degrees of freedom are fully actuated. It walks and carries the wearer and its own power supply, and it is designed to assist the wearer's muscles using EMG signals. The device's height is 1.6 meters and it weights 23 kg; the accumulators allow an autonomy 160 minutes of continuous motion and enable the exoskeleton to hold up to 70 kg. The upper body weights 8 kg and the lower part weighs 15 kg. The patients (wearers) are attached to HAL at the pelvis with a harnesses, and at the level of calf and thigh using rubber belt. HAL's structure doesn't transfer the load to the ground, but, it adjusts hip, knee and ankle power to increase the wearer's holding capability. The joint measurements are provided by potentiometers.

As same as Rewalk, Ekso exoskeleton is based on actuation -in sagittal plan- on the level of the Hip and knee by servo-actuators and also the wearer use crutches to secure balance during motion. The device itself weights 20 kg and its walking speed is 3.2 km/h as maximum. On the other hand, its autonomy is 180-480 minutes. And also, Ekso executes sit-to-stand and stand-to-sit tasks and walk in a straight line successfully.

Indego plays a role of active orthotics for rehabilitation objectives. It has the hip and knee joints as actuated degrees of freedom in sagittal plan only, while actuation for the ankle joint is not presented. The lower limb joints are actutated by DC motors through a notable gear reduction and can produce a 12 N.m as continuous torque. The power supply is made from lithium polymerm and it achieves a 60 minutes of the system autonomy. The device support patients weighting up to 91 kg, while it weighs only 12 kg.

Phoenix exoskeleton (child size) made by university of California, its objective is to recover the motion of the paralyzed children. Phoenix is quasi-adjustable on the knee and hip levels, a battery system can achieve an autonomy of 240-840 minutes, the phoenix users can have a height between 160 cm and 187 cm while the weight of should not exceed 91 kg, while it weighs 12 kg. Range of motion is limited to 35^{o} at the hip and 20^{o}at the knee, also the user need to use the crutches to achieve stability.

BLEEX system aims to human power augmentation[12]12, 13], because its capability of carrying its own weight plus an external payload [14]. The power supply of the device is independent, BLEEX can walk with speed of 3.6 Km/h and it can carry 34 kg as a payload and the weight of the wearer and the structure.

The ranges of motion (ROM) of each joint are illustrated inTable 1. Each leg has 7 hydraulically actuated degrees of freedom, three on the level of hip, one at the knee and three at the ankle.

Table 1: Specification of Bleex Joints

	Bleex ROM	Human Max Torque	Bleex Max Torque
Ankle flexion/extension	±45^{o}	-120 N.m	-200/155 N.m
Knee flexion	121 ^{o}	-35/60N.m	-100/140N.m
Hip flexion/extension	±121 ^{o} /10 ^{o}	-80/60 N.m	-150/130N.m

Power needs, range of motion, and applied torques, are taken from human bio-mechanical analysis based on the several following parameters: 75-kg as weight, walking on flat ground at roughly 1.3 m/s. The joints available ROM was designed to be less than the human normal ROM for safety; however, some joints' range of motion had to be reduced to avoid (mechanical) singularities.Thus, an exoskeleton that can regenerate the walking and all the other activities of children needs,in order to recover the autonomous feeling of the children patient, is still an open question till now. The literature reviewinform that there is no developed portable lower limbexoskeleton of patients with neurological disorders and stroke witch could lead to new functional rehabilitation, mobility-aid, and re-educatuion methods.

3 STUDY ON THE GAIT CYCLE PROPERTIES

The ordinary human leg has seven Degrees of freedom: three on the hip, three for ankle, and one on the knee, the degrees of freedom on the level of toes are not considered in our study; this geometrical collection of degrees of freedom allows human to carry out complicated movements and actions, which, in turn, give human capability to maneuver and balance

The human bones and muscles act during his motion, both when walking or any other physical activity. To understand the movements of the human body, the motion in each of the three anatomical planes should be taking into consideration, seeFig. 1, but, based on daily activities and the gait kinematics for the paralyzed patients (walking, sitting down, standing up...etc.), the most used plane of motion is the Sagittal plane among the two other planes.

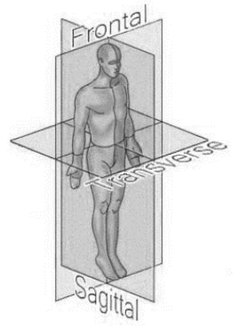


Fig. 1.Anatomical planes

Among the human daily activities, the walking is the most important regular task to do a lot of manipulations that everyone need. A normal walking gait is a periodic physical activity, which is bounded by two heel strikes for the same leg. In general a gait cycle is divided into two phases: swing and stance phase. The stance phase is the phase when the body weight is supported by one leg (right leg as shown inFig. 2,starting from the heel strike of the concerned leg and finished at the heel strike of the other leg. While the swing phase is the period of time when the first leg is returning to its initial position for the next heel strike, and therefor, for the next gait.

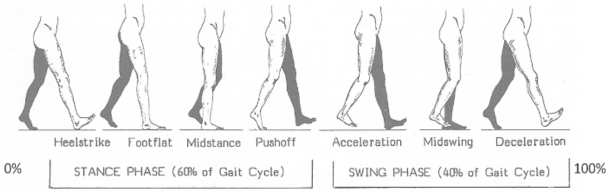


Fig. 2. Complete gaite cycle [15]

At the normal stability phase, the body is supported by the two legs (double supported) so the load is supported by the two leg at the same time, but by the beginning of the walking, the weight of the whole body will be transferred to the heel stroked leg. The shock created by the changing in load distribution is absorbed because of the rapid transfer period of the load.

After examining the characteristics of the hip and knee joints during normal gait motion, we came to the following results: the hip's ROM is from -20° to 28°, while on the level of the knee are starting from 0° to 64° (see Fig. 3).

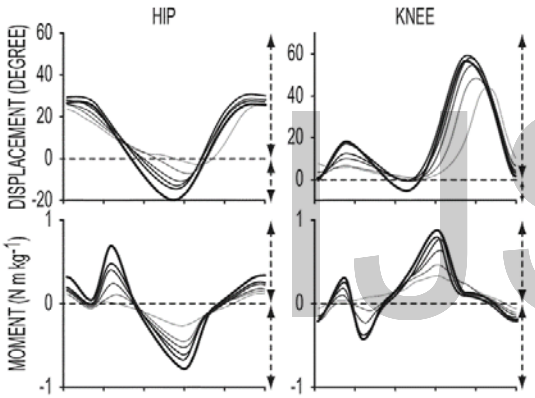


Fig. 3. Angle and torques for hip and knee joints with respect to gait cycle, Trajectories are for six walking speeds ranging from 1 to 1.6 Km/h [16].

To calculate the required angular speed for the both hip and knee joints to perform a gait cycle, a differentiation of the angles with respect to time as shown in Eq. (1) is needed.

$$\omega = \dot{\theta} = \frac{d\theta}{dt} \tag{1}$$

To apply the differentiation to get the required speed, a simpleMatlab-Simulink® model as shown in Fig. 4is needed, the feeding of data is carried out with 0.1 time step to be differentiated with a conversion from deg/s into rpm.

After consolidating the data (angle, speed, and torque) of the hip and knee, the following charts are concluded see Fig. 5. Knee and Hip torque curves are calculated using the normalized charts per unit mass as shown in Fig. 6.

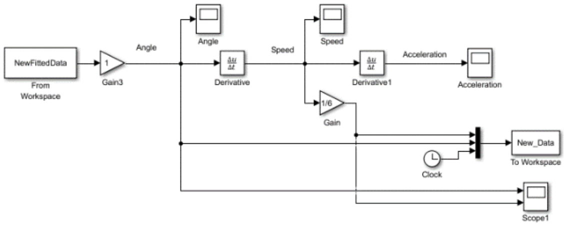


Fig. 4. Matlab-Simulink® model to calculate hip motion curve derivatives

Table 2summarize the speed and torques required for knee and hip joint during the gait cycle based on the obtained normalized charts (see Fig. 5, and Fig. 6) on a specific walking speed 1.4 km/h.

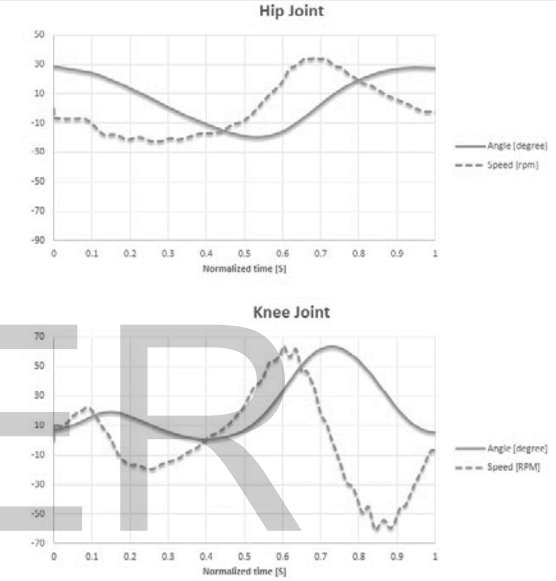


Fig. 5. Angles, and speeds for hip and knee curves w.r.t. gait cycle.

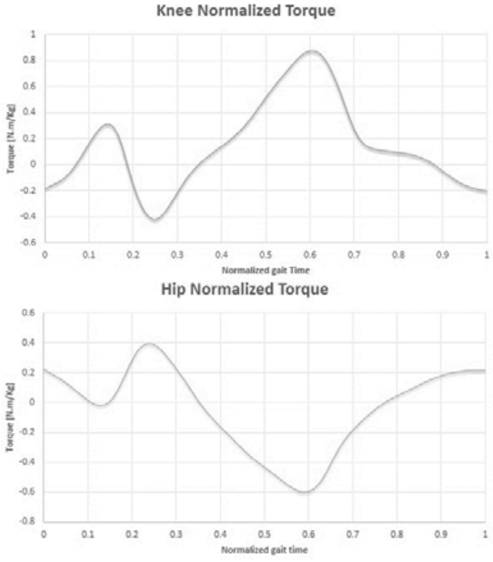


Fig. 6. Hip and knee normalized torques per unit mass w.r.t. gait cycle.

Table 2: Normal Gait Properties

	Angle	Speed [rpm]	Torque

	[deg]		[N.m/Kg]
Hip Joint	-19/28	35	0.6
Knee Joint	0/64	63	0.88

Suggested Exoskeleton

The proposed active orthotic device is physically attached to wearer's lower limbs by a collection of belts and harness[17], the crutches are planned to be used to maintain balance. It contains four actives degrees of freedom, tow for the left and right hips and two for left and right knees, while the ankle joint is not actuated, and it is supposed as a passive joint for motion compensation. The exoskeelton system also contains a back pack to integrate into it the accumulators, the on-board computers to perform the high level control, the microprocessors, servo actuators' drivers, inclinometers to measure body motion, etc.

Exoskeleton Parameters

The system parameters are listed below, as shown in Table 3Body weights and lengths are gathered from an exsiting medical report, when the other paramerts are estimated based the literature [18]. A safety factor is necessary for some data for better system durability (≈6%).

Table 3: Body and System Parameters

Weights		
Mass of the whole Body	50	[kg]
Mass of upper Trunk (with Head and Arms)	29.1	[kg]
Mass of Backpack	15	[kg]
Mass of upper Trunk + Backpack	44.1	[kg]
Mass of Leg	10.4	[kg]
Mass of Thigh	7.39	[kg]
Mass of Shank	2.4	[kg]
Mass of foot	0.65	[kg]
System Mass at the HIP (per each)	2.5	[kg]
System Mass at the Knee (per each)	2.5	[kg]
System Mass at Thigh	1	[kg]
System Mass at Shin	1	[kg]
System Mass at Foot	1.5	[kg]
Total System Mass for one Leg	8.5	[kg]
Total System Mass	32	[kg]
Total Body and System Masses	82	[kg]
Lengths		
Total length of Body	1.4	[m]
Trunk length	0.63	[m]
Leg Length	0.77	[m]
Thigh Length	0.34	[m]
Shin Length	0.42	[m]

4 THE UNIFIED ACTUATOR SIZE CALCULATION

To calculate the required power for each actuated degree of freedom, and to select servo DC motor which will generate the motion on each joint, the worst case conditions of the applied load on the joints (quasi-static situation, and without any crutch support) are considered and will estimate the maximum torque needed each joint as well as and maximum angular speed.

4.1 Torques Applied on the Hip

The Needs

The swing phase for the leg consists of supporting the total weight of the upper body of the wearer and the backpack when they are tilted forward up to 40º.

Considered Assumptions

- The wearer body width in sagittal plane will be considered 0.2 m while backpack thickness is 0.15 m.
- The hip center of rotation is below the center of gravity of the upper body by 55% of upper body height.
- The centroid or the center of gravity of the whole body will be located at the geometric center of both body and backpack.

The Calculations

This subsection will show the calculation the weight magnitude and geometric location of the centre of gravity for both of body and back-pack, see Fig. 7:

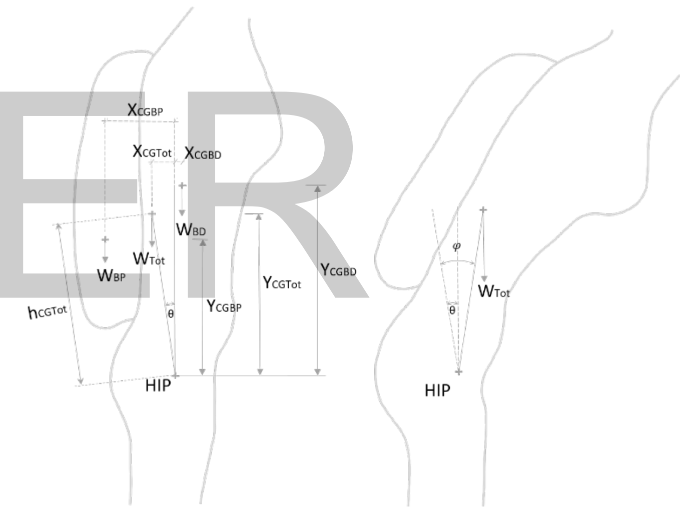


Fig. 7. Hip torque calculations.

a) The weight magnitude

$$W_{Tot} = W_{BD} + W_{BP} \tag{2}$$

Since,

$$W = m \times g \tag{3}$$

b) Location

$$W_{BD}(Y_{CGBG} - Y_{CGTot}) = W_{BP}(Y_{CGTot} - Y_{CGBP})$$
$$Y_{CGTot} = \frac{W_{BP}Y_{CGBP} + W_{BD}Y_{CGBD}}{W_{BD} + W_{BP}} \tag{4}$$

And,

$$W_{BD}(X_{CGBD} + X_{CGTot}) = W_{BP}(X_{CGBP} + X_{CGTot})$$
$$X_{CGTot} = \frac{W_{BP}X_{CGBP} - W_{BD}X_{CGBD}}{W_{BD} + W_{BP}} \tag{5}$$

So the angle (θ_{CGTot}) is calculated as follow:

$$(\theta_{\text{CGTot}}) = \text{Tan}^{-1}\left(\frac{X_{CGTot}}{Y_{CGTot}}\right) \tag{6}$$

At stand still position, the torque can be calculated as:

$$T_{\text{Hip},\phi=0^\circ} = W_{Tot} \times X_{CGTot} \tag{7}$$

Where,

$$h_{CGTot} = \sqrt{X^2_{CGTot} + Y^2_{CGTot}} \tag{8}$$

It's required to bend the upper trunk by 30°, so the torquewill be:

$$T_{Hip,\varphi\neq 0} = W_{Tot} \times h_{CGTot} \times \sin(\varphi - \theta) \tag{9}$$

Numerical application are illustrated inTable 4.

Table 4: Torque Calculations for Hip

Variable	Value	Unit	Variable	Value	Unit
Body Width	0.2	[m]	φ	40	[deg]
Backpack width	0.15	[m]	W_{Tot}	432.77	[N]
W_{BD}	285.61	[N]	X_{CGTot}	0.054	[m]
W_{BP}	147.15	[N]	Y_{CGTot}	0.33	[m]
X_{CGBD}	0.005	[m]	h_{CGTot}	0.335	[m]
X_{CGBP}	0.17	[m]	θ_{CGTot}	9.359	[deg]
Y_{CGBD}	0.35	[m]	$T_{\text{Hip},\varphi=0}$	23.587	[N.m]
X_{CGBP}	0.3	[m]	$T_{\text{Hip},\varphi=40}$	73.92	[N.m]

4.2 Torques Applied on the Hip

The Needs:

One knee should be able to support bodyweight while walking.

Considered Assumptions:

- The right knee is considered to be fixed at ground.
- The center of gravity for the leg is considered to be located near the knee.
- The Maximum Hip flexion is 10°and 20° for extension.

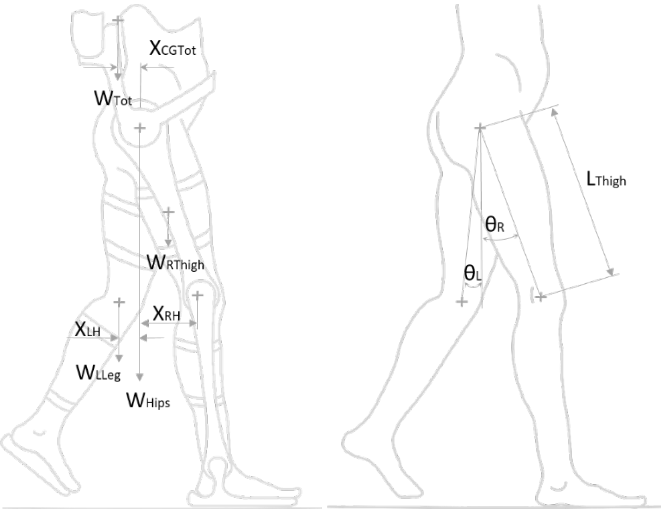


Fig. 8. Knee torque calculations during gait.

Calculations:

To calculate the sufficient torque applied on the knee during a normal gait cycle, it is important to do the calculations in the worst loads conditions. Therefore, while the entire body is held by one leg, and no crutches are presented to maintain balance or to support load. Based on the above Fig. 8, the consolidated body (wearer and exoskeleton) is held by the right leg. Hence, counterbalancing the weight of the entire body is done by the right knee.

X_{LH} is the distance between the unsupported leg (left leg) and the Hips' center, where X_{RH}represents the geometrical distance from the supported leg (right leg) and the center of Hips. In the considered legs configuration,$\theta_L$is the maximum flexion angle on the hip, and $\theta_R$is for extension on the hip level.

$$\begin{aligned} X_{LH} &= L_{Thigh} Sin(\theta_L) \\ X_{RH} &= L_{Thigh} Sin(\theta_R) \end{aligned} \tag{10}$$

The generated torques by the upper body and the backpack at the upper body center of mass are noted in the following equation.

$$\begin{aligned} T_{\text{Tot},\phi=0^\circ} &= W_{Tot}(X_{CGTot} + X_{RH}) \\ T_{\text{Tot},\phi\neq 0^\circ} &= W_{Tot}(X_{RH} - h_{CGTot} \times \sin(\phi - \theta)) \end{aligned} \tag{11}$$

Where the upper body weight is W_{CGTot} .

The torque applied on the knee, caused by the weight associated with the hips actuators W_{Hips} and located at the center of Hips, is the following:

$$T_{\text{Hips}} = W_{Hips} \times X_{RH} \tag{12}$$

The raised leg (during the swing phase) and the attached exoskeleton's structure are weighting W_{LLeg} and are located near the left knee. The both bodies will generate a torque:

$$T_{LLeg} = W_{LLeg} \times (X_{LH} + X_{RH}) \qquad (13)$$

Another torque will be manifested by the presence of the load caused by the thigh and the attached exoskeleton structure:

$$T_{RThigh} = W_{RThigh} \times \frac{X_{RH}}{2} \qquad (14)$$

The results of (11), (12), (13), and (14)lead to this general torque applied on the knee in the worst conditions of load:

$$T_{Knee} = T_{Tot} + T_{Hips} + T_{LLeg} + T_{RThigh} \qquad (15)$$

Applying the numerical values, the results will be generated in Table 5

Table 5: Torque Calculation for Knee

Variable	Value	Unit	Variable	Value	Unit
θ_L	10	[deg]	X_{LH}		[m]
θ_R	20	[deg]	X_{RH}		[m]
W_{Tot}	432.77	[N]	$T_{Tot\varphi=0}$		[N.m]
X_{CGTot}	0.05	[m]	$T_{Tot\varphi\neq0}$		[N.m]
W_{RThigh}	82.305	[N]	T_{Hips}		[N.m]
W_{LLeg}	161.3	[N]	T_{RThigh}		[N.m]
W_{Hips}	49.05	[N]	T_{LThigh}		[N.m]
L_{Thigh}	0.347	[m]	$T_{Knee,\varphi=0}$		[N.m]
			$T_{Knee,\varphi\neq0}$		[N.m]

4.3 Angular Velocity Calculation of the Hip

Taking into account the walking frequency in one second is 1 complete cycle, the gait is starting from 0% to 100% as shown in Fig. 2.

During gait cycle, and based on the bio-mechanical data as shown in Fig. 5, it is remarked that the maximum hip angle is 35^{o} for healthy adult man. In the other hand the proposed exoskeleton is planned to have a maximum hip motion angle is 20^{o}, so the data gathered from the normalized data should be scaled to decrease the maximum hip motion, before applying differentiation process.

After scaling and differentiation Fig. 9, the maximum angular velocity is indicated as approximately 21 rpm and this occurs at instant 0.7s.

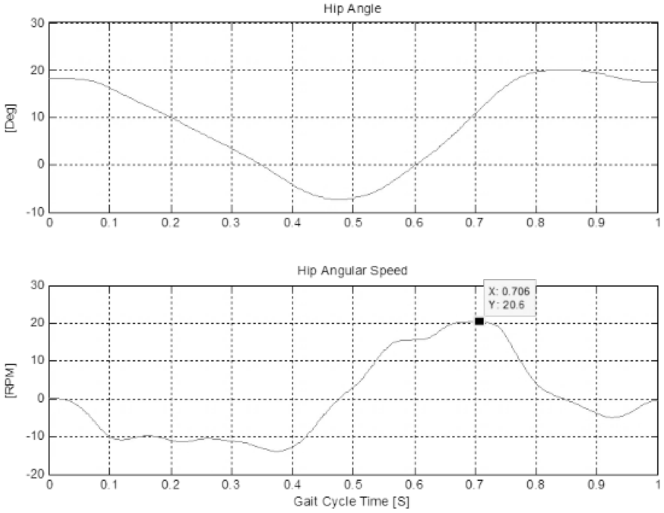


Fig. 9.Hip Degree of Motion curve.

4.4 Knee speed calculation

In order to obtain the angular velocity curve for the knee joint, scaling and differentiation with respect to time have to be done on the knee motion normalized curves.

From Fig. 10, it's remarked that the maximum velocity required for knee joint is about 34 rpm, and that happens at 0.5 s of the gait cycle.

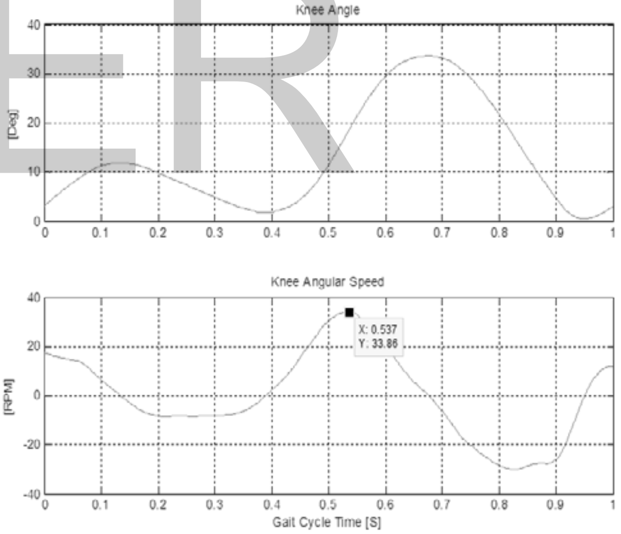


Fig. 10. Knee Degree of Motion curve.

5 THEORETICAL RESULTS

The calculations done before can summarize and present the results shown in Table 6.It's obviously shown that the knee joint actuators must be powerful than those installed on the hip. Hence, to start designing the exoskeleton device, several constraints are presented on this point such as (the simplification of mechanical system, the system durability, the ability to do multiple tasks and physical activities...etc.). So the use for a one type of servo actuator that can fit the both degrees of freedom (hip and knee), and that can help the wearer to do several daily activities and can perform several scenarios (sit to stand, stand to sit, climbing stairs...etc.) using the crutches. Therefore, the proposed powerful servo actuator should satisfy each joint requirements, so it should be able to overpass a 130 N.m torque, and its angular speed shouldn't be less than of 35 rpm.

Using a directly driven servo actuator on each joint will simplify the geometry of the skeleton, and will offer several advantages:At the level the lengths of the links relating the hips and knees so the exoskeleton can grow with the wearer till the next age level. Besides, this design will obviate for the use of extra mechanical parts such as supports, transmission belts, bevel gears, worm gears, bearings ... etc.

Table 6: Max Speed and Torque for Hip and Knee

Actuated Joint	Required Torque [N.m]			Max Speed [rpm]
	From Curve	Calculated	Difference %	
Hip	0.6 x 82=49.2	51.128	≈104%	21
Knee	0.8 x 82=72.1	123.58	≈173%	34

6 EXOSKELTON MODELLING

To test and validate the obtained results using Matlab-Simulink®, a virtual model is constructed to simulate the exoskeleton performing gait cycle. The latter model shown in Fig. 11 is designed and imported using the software CATIA®. CAD files where not only used for manufacturing and assembly procedure, but also in developing a dynamic model on Simulink – Matlab. As the CAD files for the exoskeleton parts have the perfect dimensions and material specifications, thus Simulink could make use of weight, center of mass (COM), and inertia estimated measurements for each element of the exoskeletal-system.

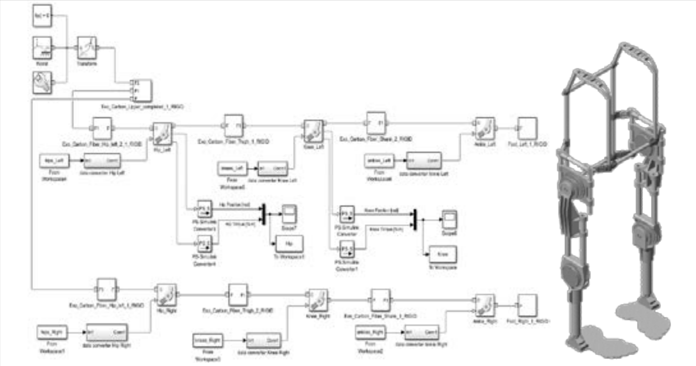
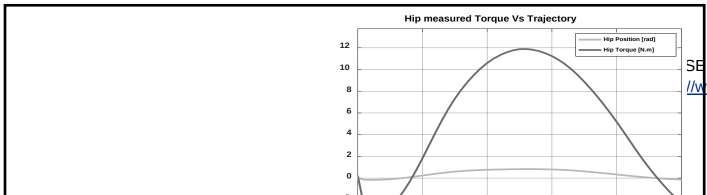


Fig. 11. Exoskeleton model programming and visualization.

Also mechanical limits, constrains and joints were defined in the model, as well as the system has three DOF per leg, the model could acquire the trajectory for each DOF, and the corresponding required torque could be measured. The gait cycle trajectories had fed to the model to measure the torque necessary to drive the exoskeleton on the fly. That was necessary to give a figure about the power loss in driving the system on the fly.



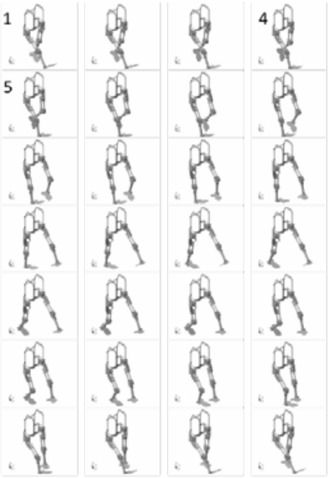


Fig. 12. Simulation Results.

Model development and enhancement is still in progress to incorporate the ground reactions, and hence, the availability to verify the ability of the exoskeleton to drive itself in addition to its load (patient) would be accomplished.

7 CONCLUSION

As a conclusion on the presented work, the proposed device represents a highly adjustable child size exoskeleton that can grow with the patients. Therefore, it should be simple, lightweight, adjustable, and able to provide the required power as well, to enable children to apply gait motion at the very first time. Hence, two direct actuators for each leg will maintain the needed simplicity, in addition using composite material in the thigh and shank will decrease the device's weight, also allowing the device to have affordable in price.

The load calculations are based on the worst case condition (quasi-static situation), and they are applied respecting the anatomical body dimensions. since comparing to the scaled and normalized bio-mechanical data the quasi static torques has established a notable difference between the two values, the calculated torques are considered to design the direct servo actuators. On the other hand, actuators speed curves, are calculated after scaling and differentiating the joint motion trajectories.

At last, testing and verification process is done using a virtual model of the child wearing exoskeleton and performing a normal gait. The results conclude that the selected operation parameters are sufficient enough to perform the gait cycle.

FUTURE WORK

The future tasksconcerning the development of the exoskeleton focuses on several points: on establishing more advancement in technologies such as accumulators, servo-actuators, and durablegearboxes. Also, there are some points associatedwith the exoskeleton design like understanding the muscle’s behavior withinthe gait cycle and another activitesto optimise the mechanical properties of exoskeleton. Another important point need to be treated, concerning exoskeleton’s interface to the patients on both mechanical and control wise. Finally, the safety of the device's wearer need to be studied since the patients are insidea powerful exoskeleton and they couldn't support any unexpected motion of this exoskeleton.

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