Technical Report for Professional Interview

Prepared by: Dr Rizauddin Ramli

Department of Mechanical and Material Engineering,
Faculty of Engineering & Built Environment,
Universiti Kebangsaan Malaysia,

Development of servo controlled Reciprocating Gait Orthosis(RGO)

---

1. Introduction

Nowadays, we are exposed to various types of chronic illnesses and accident. Unexpected accidents and illnesses can cause permanent changes in body and certainly affect the quality of a person's life. However with the advances in health, medical treatment and technology enable people to survive and live longer. For example, patients with spinal cord injury normally require a long time to recover and in the same time need to adapt rehabilitation treatment persistently.

One of the reasons which is causing the paraplegia is because of the breakage in motor or sensory function of the lower extremities due to complete or incomplete spinal cord injury, which may cause by accident or other illness [1]. The paraplegia patients with non-permanent disabilities always have tendency to walk again and are advised for rehabilitation therapy [2]. With today's modern technology, various types of orthoses and support tools have been designed in order to help the paraplegia patients in their rehabilitation treatment. An orthosis is a tool that usually used for patients with paralysis of legs or paraplegia patients for their recovery and mobility purposes.

For example, there are many orthopedic devices such as Knee-Ankle-Foot Orthoses (KAFOs), Walkabout Orthosis (WO), Hip-Knee-Ankle Foot Orthoses(HKAFO), Total Knee Arthopastry (TKA), Reciprocating Gait Orthoses (RGO) have been developed and commercialized. According to a study by Carina et al.[3], RGO is a device consists of a trunk support, a pelvis band and bilateral knee-ankle-foot othoses which are connected with dual-cable movable hip joint. The coupling of both hips gives hip stability during standing by preventing simultaneous flexion. Flexion in hip activates the cable system to extend the contralateral hip and permitting ambulation. Disconnection of hip and knee joints permits simultaneous flexion for sitting.

Jefferson et al. [4] studied pattern of movement, hip joint motion, and general gait parameter for the three type of orthosis which are Hip Guidance Orthosis(HGO), Reciprocating Gait Orthosis(RGO) and Steeper's Orthosis. Observation that hip abduction in HGO is greater than other two devices and this makes HGO more suitable for the use with crutches. RGO and Steeper's orthosis could achieve stride length entirely by degree of flexion or extension at hip joints. Although these two orthoses show similar pattern and movement, Steeper's orthosis made sitting and standing much easier with corresponding advantages to patients. Solomonow et al. [5] found that RGO powered with electrical stimulation of thigh muscles as secondary rehabilitation phase (RGO II) benefits patient paraplegia. After a couples of time using the RGO II, most of the patients could walk independently on grass, ramps and curbs, don and doff, stand up from seated position, ambulate at least 180m, all without assistance. The RGO II were performed with this objective, allowing paraplegics to put on and use the orthosis at any time without expecting an assistance. Besides, regular use of RGO had a general positive impact on the patients' health and outlook.

In addition, there is another research regarding Powered Gait Orthosis (PGO). PGO is a modification of an RGO, incorporating two pneumatic muscle actuators (PMA), a compressed air system, and pressure and joint angle sensors. Each hip joint of the PGO is flexed by an air muscle operated by pressurized air, enabling the patient to walk. In the PGO gait, since the hip joint is flexed by the air muscle and not by the rotation of the trunk, the movement of the center of the body appears to be more stable than that of the RGO gait [6]. There is a comparison study among different types of orthoses that has been carried out by Abe in 2006[7]. The study showed that the RGO demonstrate a superior performance in the terms of static equilibrium, walking velocity and energy consumption compared to Knee-Ankle-Foot Orthosis (KAFO) and Walkabout Orthosis (WO). Paraplegia patients had significantly superior balance maintenance capability when they are using the RGO rather than when they are using the WO or KAFO. This superior capability may be attributed to the stability of anteroposterior and lateral directions in pelvis and hip joints. Maintenance of paraplegic standing depends on the iliofemoral ligament with hyperextension in the hip joint. However most of the orthoses above are called a passive orthotic devices or passive RGO which means it must be moved with high energy by paraplegia patients.

Therefore, in this report, a development and design process of a servo controlled reciprocating gait orthosis (RGO) to assist paraplegic patients for their rehabilitation treatment is presented. There are at least three main problems faced by the current passive RGO need to be addressed.

1- The design of RGO is complicated compared to other orthoses. It is due to the difficulties of wearing and removing the device especially for children. The RGO normally is a mechanical device which needed to be moved by user with the help of clutches.
2- Higher energy consumption is required for the users.
3- The manufacturing cost of a RGO is expensive because the size of RGO is highly depended on the size body of user.

The main objectives of developing the RGO are to design a simple, easy and friendly user structure RGO and to minimize the energy consumption of RGO users. Also the aim is to fabricate a RGO by using at minimum cost.

In the design of the RGO, an anthropometric data provides a useful guidance to determine the size of structure. According to a survey conducted by Karmegam et al. [8], the mean weights is 72.57kg for Malays, and for the Chinese and India is 64.17kg and 65.32kg respectively. The survey was carried out at the age of 18 years to 24 years of respondents. So, this becomes the reference for the design of the RGO size. Table 1 shows a comparison in terms of weight and height among the three major races in Malaysia.

Table 1: Comparison in terms of weight and height among the three major races in Malaysia.

Characteristic	Male			Female		
	Malay	Chinese	Indian	Malay	Chinese	Indian
Weight (kg)	72.57	64.17	65.32	57.97	55.82	55.59
Height (cm)	178.57	169.38	168.1	153.3	158.58	156.83

(Source : Karmegam et al. 2011)

2. Design Process

The design objective of servo controlled RGO is to build a prototype that will possess the ability to help paraplegia patients in their mobility option. Servomotors are used for mobility purpose, and it is designed in simple structure. Therefore in this study, the design concept and analysis is playing the vital role before fabricating the prototype of the servo controlled RGO.

First, a lot of information about function and designs of RGO has been investigated through literature review, patents, catalogs and online study. **Table 2** shows various type of orthosis that have been considered as comparison. Next, in order to generate design concept to perform each major function of RGO, a brainstorming section is held and a sketch of the initial design of each structure is done.

Multiple design concept generation will lead us subject them to an evaluation scheme in order to determine the best concept. Morphological chart method is used to uncover combinations of ideas and Pugh's concept selection method helps to evaluate and compare among the ideas generated [9]. The next stage is where design concept is invested with physical form which is called embodiment design. Form of parts will satisfy the required functions of RGO. The parametric design of this RGO is depended on the anthropometric data. The structure part of RGO is designed symmetry except foot plate. When the conceptual design and embodiment design are established, drawing of all parts in RGO is constructed by AutoDesk Inventor Professional 2010. Figure 1 shows the flowchart of the development process in this study.

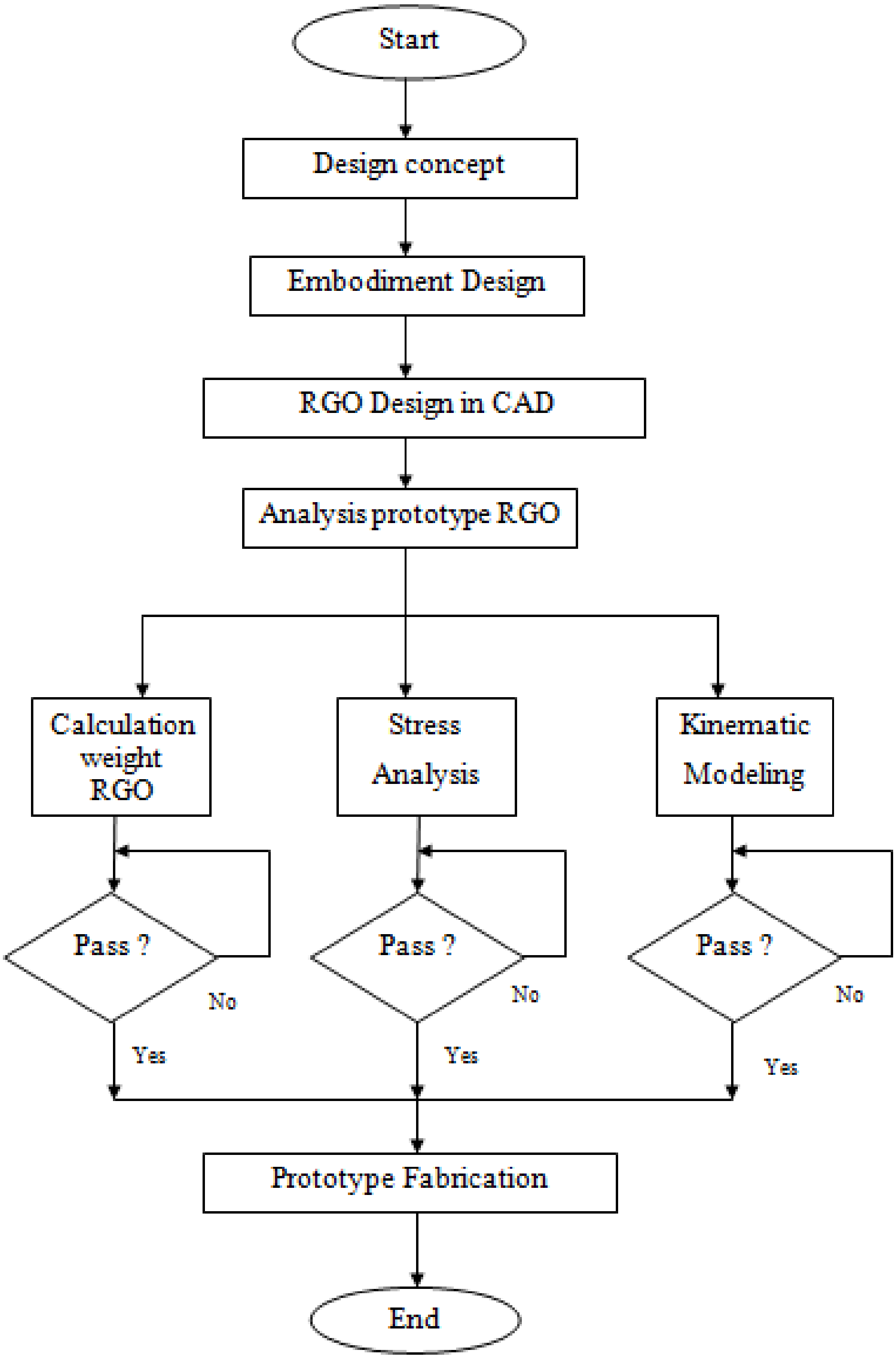


Figure 1: Flowchart of the RGO development process

An analysis of RGO design has been carried out before the actual fabrication is done. Since the one of the objective is simple and light weighted of RGO, the total weight of RGO is essential and need to be taken in consideration during design stage. By adopting the basic equation, the weight of RGO has be determined as follows.

Weight=Area x Thickness x Density of material

The material used for the fabrication RGO is Aluminium. The purpose of choosing aluminium as material for the structure of the RGO is to because to have a light weighted orthosis. This will contribute to less energy consumption of patient paraplegia.

The developed RGO consists of five main components which are waist plate, upper thigh plate, thigh plate, knee plate and foot plate as shown in Figure 2.

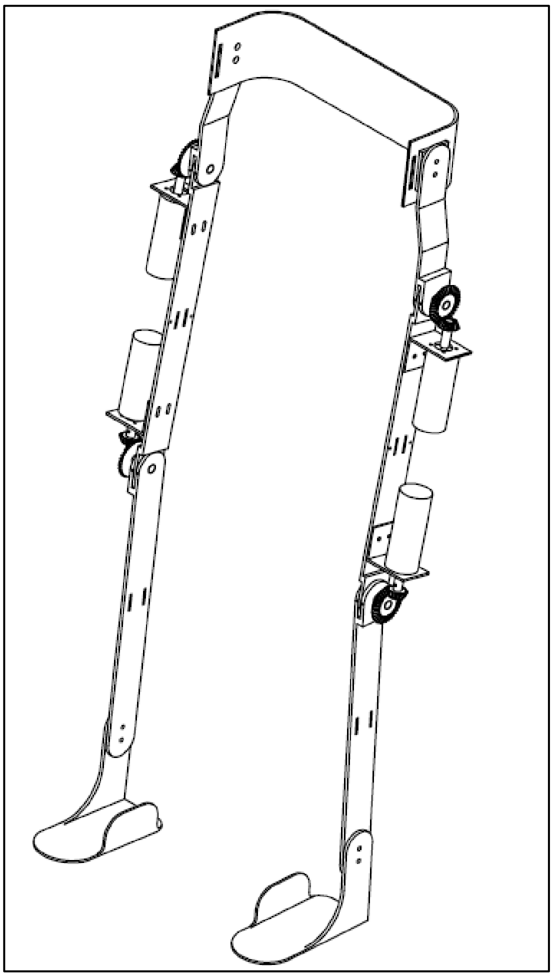


Figure 2: Complete Design of 4DOF RGO

3. Kinematic model

Kinematic modeling is carried out for the purpose of torque analysis. Figure 3 shows a 2dimension schematic view of the simplified model of the RGO structure. A reference frame {O} is set as reference point while frame {A} is attached to the foot and frame {B} is attached to the body. θ_a, θ_k and θ_h are the angles of the ankle, knee and hip.

The forward kinematic from frame {A} to frame {B} is as follows,

$$ {}^{A}_{B}X = \begin{bmatrix} x \\ z \\ \theta \end{bmatrix} = \begin{bmatrix} -L_1 \sin\theta_a - L_2 \sin(\theta_a + \theta_k) \\ L_1 \cos\theta_a + L_2 \cos(\theta_a + \theta_k) \\ -\theta_h - \theta_k - \theta_a \end{bmatrix} \tag{1} $$

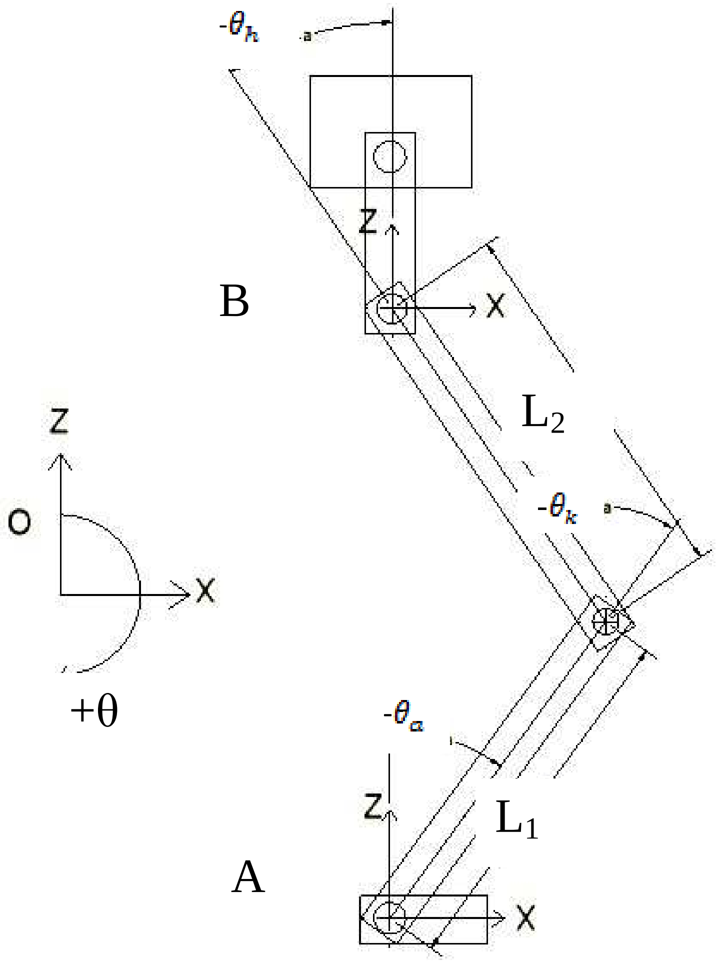


Figure 3: 2D model of single leg of RGO

In robotics, a Jacobian matrix is commonly used to represent the velocity and angular velocity. Partial differentiation of ${}^{A}_{B}X$ will produce Jacobian matrix, which is shown as below.

$$ \dot{x} = -L_1 \cos\theta_a . \dot{\theta}_a - L_2 \cos(\theta_a + \theta_k) . (\dot{\theta}_a + \dot{\theta}_k) \tag{2} $$

$$ \dot{z} = -L_1 \sin\theta_a . \dot{\theta}_a - L_2 \sin(\theta_a + \theta_k) . (\dot{\theta}_a + \dot{\theta}_k) \tag{3} $$

$$ \dot{\theta} = -\dot{\theta}_h - \dot{\theta}_k - \dot{\theta}_a \tag{4} $$

Then, Equation (2)-(4) is simplified as,

$$\begin{bmatrix} \dot{x} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -L_1 \cos\theta_a - L_2 \cos(\theta_a + \theta_k) & -L_2 \cos(\theta_a + \theta_k) & 0 \\ -L_1 \sin\theta_a - L_2 \sin(\theta_a + \theta_k) & -L_2 \sin(\theta_a + \theta_k) & 0 \\ -1 & -1 & -1 \end{bmatrix} \begin{bmatrix} \dot{\theta}_a \\ \dot{\theta}_k \\ \dot{\theta}_h \end{bmatrix} \tag{5}$$

Therefore, the Jacobian matrix is as follows.

$${}^A_B J = \begin{bmatrix} -L_1 \cos\theta_a - L_2 \cos(\theta_a + \theta_k) & -L_2 \cos(\theta_a + \theta_k) & 0 \\ -L_1 \sin\theta_a - L_2 \sin(\theta_a + \theta_k) & -L_2 \sin(\theta_a + \theta_k) & 0 \\ -1 & -1 & -1 \end{bmatrix} \tag{6}$$

By using the Jacobian matrix, the relation between frame A and B,

$${}^A_B\dot{\vec{X}} = {}^A_B J \, \dot{\vec{\theta}} \tag{7}$$

and the virtual force to joint torque,

$$\vec{\tau} = ({}^A_B J)^T \, ({}^A_B\vec{F}) \tag{8}$$

Since the ankle is un-actuated (no motor), the ankle will be constrained as the direction in which forces can be applied. So, there is a constraint which τ_a=0.

Therefore, the constrained equation will be,

$$\begin{bmatrix} 0 \\ \tau_k \\ \tau_h \end{bmatrix} = \begin{bmatrix} -L_1 \cos\theta_a - L_2 \cos(\theta_a + \theta_k) & -L_1 \sin\theta_a - L_2 \sin(\theta_a + \theta_k) & -1 \\ -L_2 \cos(\theta_a + \theta_k) & -L_2 \sin(\theta_a + \theta_k) & -1 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} f_x \\ f_z \\ f_\theta \end{bmatrix} \tag{9}$$

In this RGO, it is important to calculate the force in vertical direction and the torque. So, from Equation (9), f_x is simplified as follows.

$$f_x = \frac{-1}{L_1 \cos\theta_a + L_2 \cos(\theta_a + \theta_k)} \begin{bmatrix} L_1 \sin\theta_a + L_2 \sin(\theta_a + \theta_k) & 1 \end{bmatrix} \begin{bmatrix} f_z \\ f_\theta \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} \tau_k \\ \tau_h \end{bmatrix} = \begin{bmatrix} \frac{-L_1 L_2 \sin\theta_k}{L_1 \cos\theta_a + L_2 \cos(\theta_a + \theta_k)} & \frac{-L_1 \cos\theta_a}{L_1 \cos\theta_a + L_2 \cos(\theta_a + \theta_k)} \\ 0 & -1 \end{bmatrix} \begin{bmatrix} f_z \\ f_\theta \end{bmatrix} \tag{11}$$

If knee is fully extended, there will no virtual forces can be applied in z direction which means that θ_k=0. Therefore all the forces are admissible if knee is not fully extended. In this case, a special condition is set in order to get the estimated torque value at the joint required. The vertical force is assumed to be the weight of structure RGO. The angle of knee is set at maximum 45° meanwhile the real moment at knee and hip joint is used based on the research done by Slider et al. as shown in Table 3[10].

Table 2 : Types of orthoses and their advantages

No	Type	Structure	Advantage	Disadvantages	Source
1	RGO (Reciprocating Gait Orthosis)	Two KAFO connected together with a band pelvis	Gait walking can be done	Usage of high energy consumptions needed by the paraplegia to walk	Kang et al. 2007
2	IRGO (Isocentric RGO)	Similar structure to RGO but with *rocker bar link*	Gait walking can be done	More energy needed compared to RGO	Muller et al. 1999
3	ARGO (Advanced RGO)	Similar structure to RGO but with single link cable	Gait walking can be done	More energy needed compared to RGO	Muller et al. 1999
4	HKAFO (Hip Knee Ankle Foot Orthosis)	Having two KAFO modified with hip and pelvis joints.	Higher speed of walking	Difiiculties of standing stabilizationn	Mazur J.M 2005
5	Knee-Ankle Foot Orthosis (KAFO)	Orthosis from knee to ankle and foot	Control stability of lower extrimity	Need to walk by stilt and difficult to walk as RGO	Scheck dan Siress
6	PGO (Power Gait Orthosis)	Modification of RGO with pneumatic system	Reduce energy consumption and fatigue	Heavy	Kang et al. 2007

Table 3: Moment at lower limb of human being

	Moment(Nm)		
	Hip	Knee	Ankle
Measured	2.5	1.4	0.7
Predicted	2.1	1.2	0.4

(Source: Slider et al. 2007[10])

The length of link L_1 and L_2 of the RGO is shown in Figure 4.

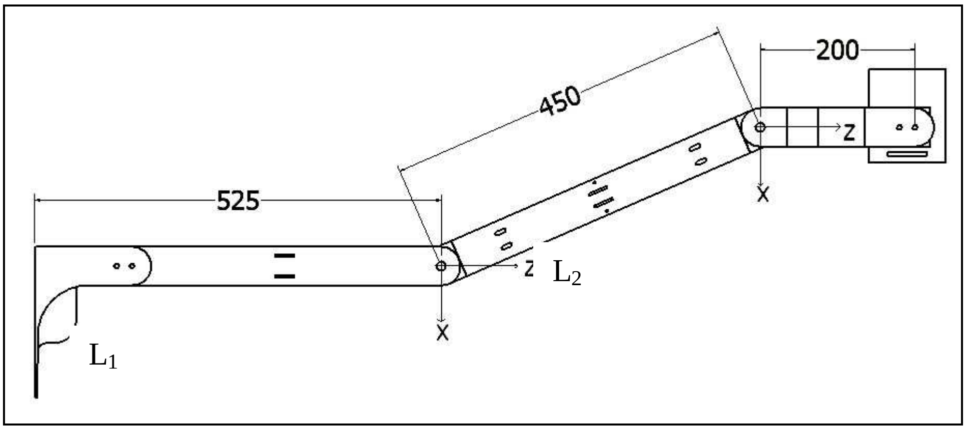


Figure 4: Two degree of freedom at each side RGO with link length (unit in mm)

4. Stress analysis

Stress analysis is carried out by using Autodesk Inventor 2010 to determine whether RGO can stand the total weight which based on anthropometric data by Karmegam et al. [8]. In this case, assumptions are made as following. The load or weight of a person is divided half and applied to the foot plate, knee plate, thigh plate and upper thigh plate. The average of a person's weight is assumed as 73kg.

The analysis on RGO structure is conducted to visual the capability of material withstand the force applied. Figure 5(a) shows stress distribution and location of stress occurs on the RGO structure. Result reveals that maximum stress (Von Mises) 37.86MPa located at each foot plate due to the force applied almost focusing at the particular part. Figure 5(b) indicates the displacement occurs when subjected to load of 73kg. The maximum displacement is 7.487mm which happen at each foot plate toward the center of RGO. The safety factor of RGO is at minimum 7.26 which mean the structural system is capable beyond the expected load.

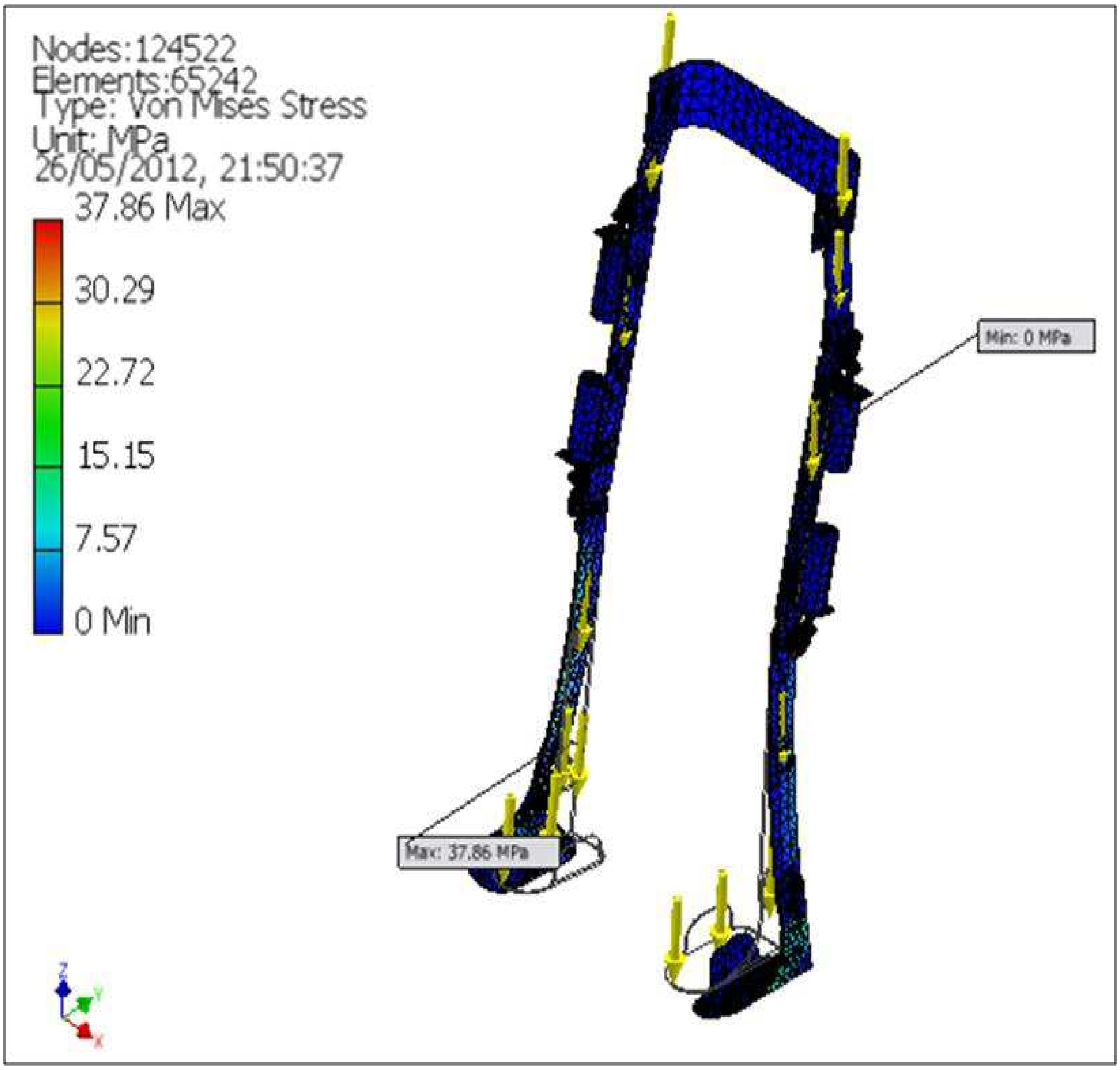
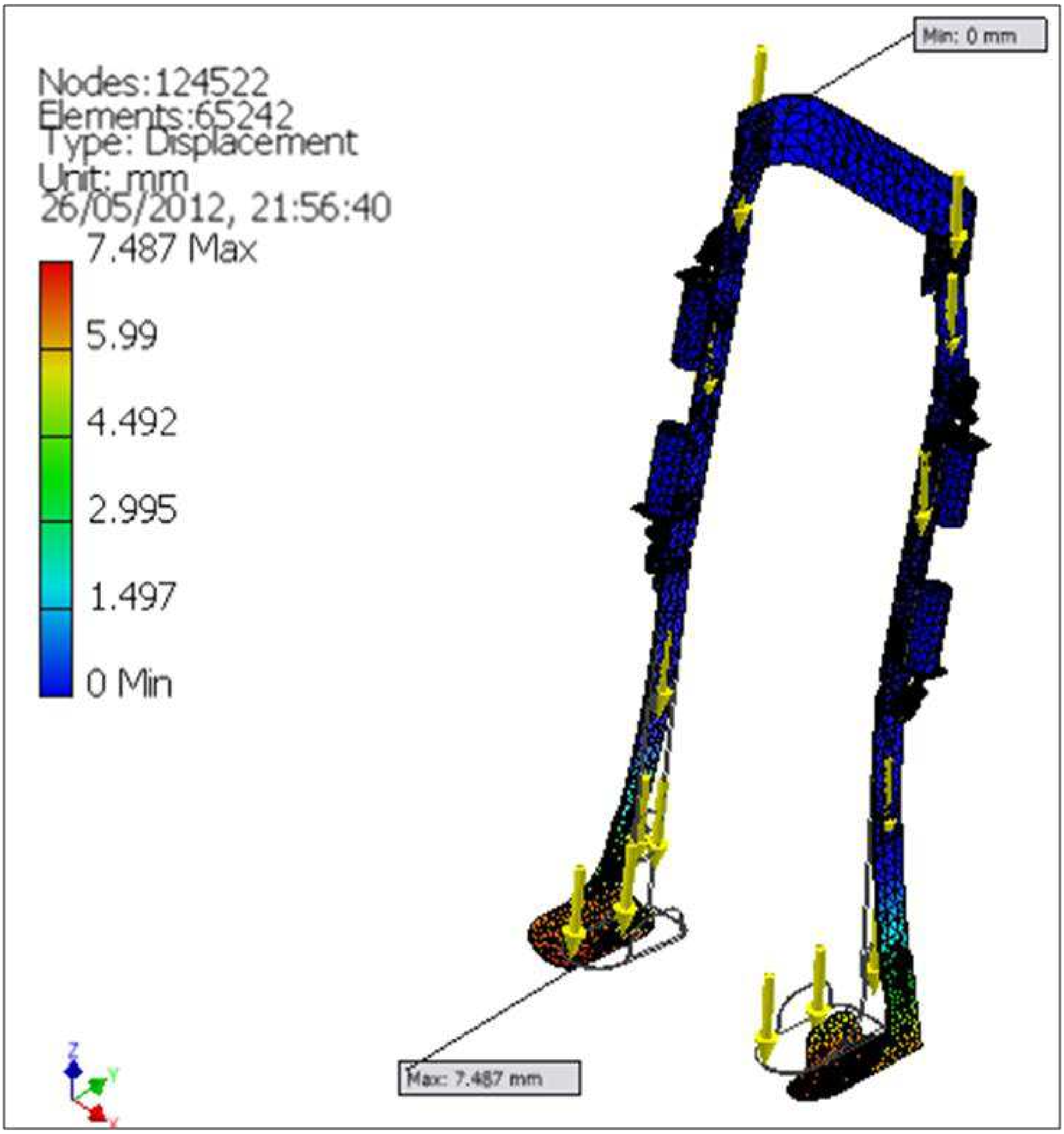


Figure 5 (a): Stress Distribution of RGO.



5 (b): Displacement distribution of RGO

Table 4: Result Summary of stress analysis

Criteria	Minimum	Maximum
Von Mises Stress	2.51×10^{-7} MPa	37.86 MPa
Displacement	0 mm	7.48748mm
Safety Factor	7.26302	15

5. Control system

Two DC servo motors are used to initiate the movement of RGO's links for each side of RGO. Data acquisition (DAQ) devices type PCI-6221 from National Instruments is used to actuate the DC servo motors accordingly based on control signal from the control system that was constructed in MATLAB Simulink as in Figure 6.

The DAQ also enable the control system to receive a feedback pulse value from servo motor's encoder that measured its position. The voltage and current of analog output from DAQ is being amplified by external power supply. The real-time application (RT) is executed via the DAQ as an interface of control system between computer and the RGO.

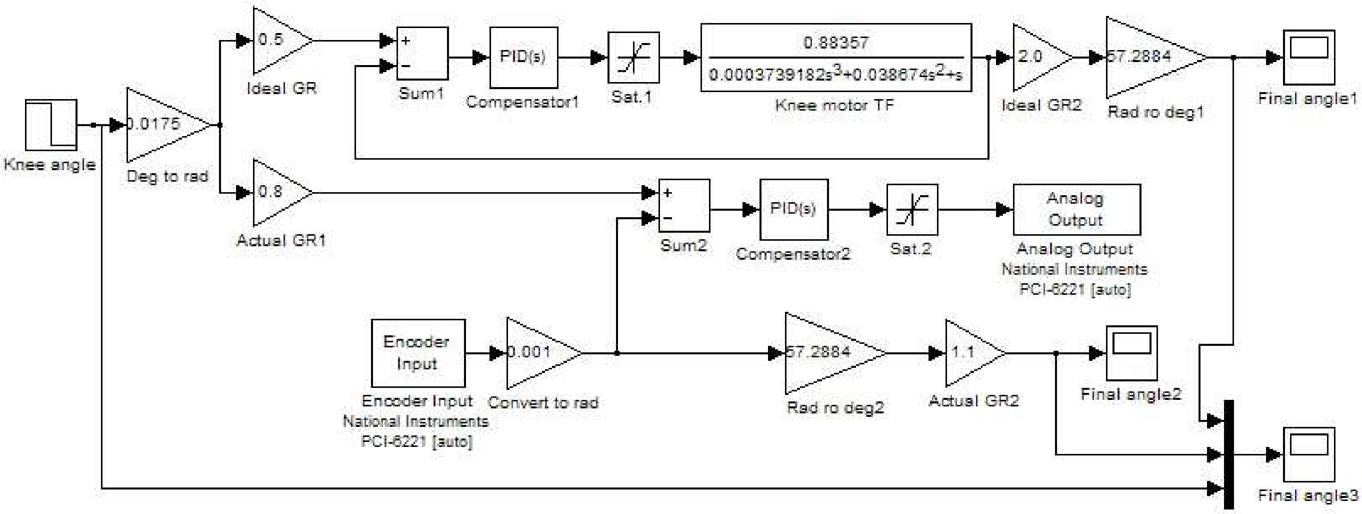


Figure 6: Close loop simulation model

6. Conclusions

The RGO that has been developed is shown in Figure 7. It is designed to be a simple, light weighted and user friendly RGO. It had four degree of freedom in the structure, with flexion at hip joint and knee joint. The usage of the DC servo motor decreases the energy consumption of the patients. Cost of manufacturing RGO is less compared to the commercial RGO in market.

References

1- Handbook of Spinal Cord Injuries, 2nd Edition, pp. 7--15, Queensland Spinal Cord Injuries Service, Australia (2001)

2- Chirazi, M.: Practical Applications of the Passive Range of Motion on the Paraplegic Rehabilitation. In: WCB 2010, IFMBE Proceedings 31, pp.985--987. Springerlink (2010)

3- Carina L. E. Gerritsma-Bleekers, Heeg, M. & Hanna Vos-Niel. 1997. Ambulation with the reciprocating gait orthosis. *Acta Orthop Scand*. 68(5):470-473.

4- Jefferson, R.J. & Whittle, M.W. 1990. Performance of three walking orthoses for the paralysed: a case study using gait analysis. *Prosthetics and Orthotics International.* 14:103-110.

5- Solomonow, M., Aguilar, E., Reisin, E., Baratta, R.V., Best, R., Coetzee, T. & D'Ambrosia, R. 1997. Reciprocating Gait Orthosis Powered with Electrical Muscle Stimulation (RGO II). Part I : Performance Evaluation of 70 Paraplegic Patients. *Orthopedics* 20(4): 315-324.

6- Kang, S.J., Ryu, J.C., Moon, I.H., Kim, K.H., & Mun, M.S. 2007. Walker Gait Analysis of Powered Gait Orthosis for Paraplegic. *World Congress on Medical Physics and Biomedical Engineering 2006*. 14: 2889-2891.

7- Abe Kaoru. 2006. Comparison of Static Balance, Walking Velocity, and Energy Consumption with Knee-Ankle-Foot Orthosis, Walkabout Orthosis, and Reciprocating Gait Orhtosis in Thoracic-Level Paraplegic Patients. *Journal of Prosthetics and Orthotics* 18(3): 87-90.

8- Karmegam, K., Sapuan, S. M., Ismail, M. Y., Ismail, N., Shamsul Bahri, M. T., Shuib, S., Mohana, G. K., Seetha, P., TamilMoli P. & Hanapi, M.J. 2011. Anthropometric study among adults of different ethnicity in Malaysia. *International Journal of the Physical Sciences* 6(4): 777-788.

9- Dieter, G.E. 2000. Engineering Design: A Materials and Processing Approach 3rd Edition. New York:Mc Graw Hill

10- Silder Amy, Whittington Ben, Heiderscheit Bryan & Thelen Darryl B. 2007. Identification of passive elastic joint moment-angle relationships in the lower extremity. *Journal of Biomechanics* 40:2628-2635.

Figure 7: Actual RGO after fabrication and assembly