Development and control of a low cost Exoskeleton system with an interactive HMI designed for paraplegic children

Elouarzi Abdelkarim, Sedra Moulay Brahim

Abstract: This article sheds light on the design and control of a lower limb exoskeleton system named NOD-P developed to assist paralyzed children with neurological diseases such as spinal cord injury (SCI) to move their lower limb and perform a gait motion. The device consists of a powered robotic device capable to operate effectively and synchronously with the human muscle-skeletal system. First, the mechatronic design presented and detailed. Second, a closed loop control system for exoskeleton developed and simulated using Matlab-Simulink. In the end, a novel human machine interface presented to ensure an interactive interface between the patient and the exoskeleton.

Index Terms: Exoskeleton children, paraplegic children, Wearable Robotics, rehabilitation, Embedded System, handicap, disabled child.

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1. INTRODUCTION

Walking is a major feature of living creatures that moves them from one geographic location to another. The ability to walk on two legs distinguished the first hominids from other apes, this transition happened over 3.5 million year ago, it allows males to free their arms and hands to gather food, plant crops, hunt and reach high objects [2]. Due to several causes (SCI, CP, accident, war, trauma, stroke…etc.), human being may lose this characteristic. As a result, individuals suffers from loss of independence in mobility, which affects their integration into the community and leads to a decreased in quality of life [3]. This effect is more obvious with children, the gait contributes not only in their mobility, but also to the safety of their physical growth, ensure their psychological state and improve their physical health and overall well-being. However, millions children from all over the world suffer from paralysis of the lower limbs. The traditional solution adopted is to use manual or electric wheelchair. This solution may solve partially the problem, but it still limits their freedom, especially when accessibility is lacking [4].

The new technology drive the disability to an alternative solution. Wearable exoskeleton suit, a powered orthosis aid disabled child to stand up and walk in school, in street and other places. This revolutionary technology has shown effective performance for paralyzed children.

2. LITERATURE REVIEW:

The first design of a system similar to an exoskeleton invented and patented in 1890 in Russia by NICHOLAS YAGN [5]. It is a spring bow system (fig.1) running parallel to the legs, it was designed to facilitate walking, running and jumping. During the late 1960s, General Electric Research and Cornell University constructed an exoskeleton’s prototype [6] called Hardiman (fig.2) "Human Augmentation Research and Development Investigation". The design was a huge machine (680 kg, 30 DOF) with hydraulic actuator that included components to amplify the strength of the arms and legs of the wearer. It was proposed to amplify human power. In 2008, the Japanese company Cyberdyne launches HAL [7] the first exoskeleton oriented to paraplegic persons (fig.3). It allows people with lower limb disabilities to perform routine ambulatory functions, stand up and climb stairs. In 2011, the company Argo Medical Technologies released a second design of the wearable exoskeleton named ReWalk [8] (fig.4). In the same year, the US Company Berkeley Bionics launches eLEGS (fig.5) "Exoskeleton Lower Extremity Gait System" [9], another hydraulically controlled exoskeleton system that allows paraplegics patients to stand up and walk using a crutches or a walker. In 2014, the American company parker started marketing the Indego exoskeleton (fig.6), designed by the Vanderbilt University Mechatronics Center in the United States [10]. In the same year SuitX declares another version of Phoenix exoskeleton (fig.7), a modular exoskeleton uses only two motors to assist paraplegic patients in walking [11]. In 2015, the company ExoAtlet [12] unveils the first medical exoskeleton of the Russian Federation fig.8. It is developed for rehabilitation and personal use. Other exoskeletons are still in the research phase or in the preclinical phase.

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Wandercraft (fig.9) is a European research project; it aims at developing an exoskeleton that allows paraplegics to walk without crutches [13]. The first commercialization was scheduled in September 2018. BioComEx (fig.10) is a research project at Suleyman Demirel University in Turkey [14]. Marsi Bionics Spanish company presents the exoskeleton Atlas 2030 (fig.11) for children with spinal muscular atrophy [15]. Another solution Exo-H3 (fig.14) developed and marketed by the Spanish company Technaid [16]. In Taiwan, the ITRI Industrial Technology Research Institute developed the exoskeleton 2WA-EXO (fig.12) [17]. The Chinese University of Hong Kong is also developing another prototype of exoskeleton named CUHK-EXO [18] (fig.13). These solutions are still in the preclinical phase. The company hocoma presents the exoskeleton LOKOMAT fig.13, it is an exoskeleton intended for the reeducation center [19].

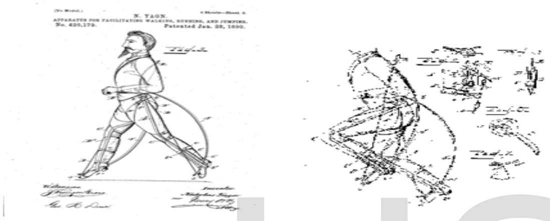

fig.1 Nicholas Yagn

Fig.2 Hardiman

fig.3 HAL

Fig.4 Rewalk

fig.5 eLEGS

Fig.6 Indego

Fig.7 Phoenix

Fig.8 Exoatlet

Fig.9 Wandercraft

Fig.10 BioComEx

Fig.11 ATLAS 2030

Fig.12 2WA-EXO

Fig.13 CUHK-EXO

Fig.13 LOKOMAT

fig.14 Exo-H3

Despite the presence of these various exoskeletons solutions, their use remains limited to the rehabilitation center or rich patients, the price of exoskeletons varies between 30,000$ and 200,000 $, the patients in poor countries cannot afford to obtain such solution, and this fact encourages us to develop a cheap exoskeleton named NOD-P for the paraplegic children in poor countries.

3. MECHATRONIC STRUCTURE:

The current solution geared towards paraplegic children in developing countries; the mechatronics system must be light, robust, practical, easy to use and as cheaper as possible: decreasing the price result increasing the number of users. The developed system displays an incorporation and interdependence of mechanical design, electronic circuit, sensors, control engineering, embedded programing and user interface. Each joint powered by a DC maxon motor (DCX 35 L Ø35 mm, Graphite Brushes), and planetary gearbox (GP42C 156: 1). Bevel gears (Module 1.5, 16 teeth) convert the direction of movement between axes. A potentiometer placed into the articular axis to capture the rotation angle of the joint figure 15.

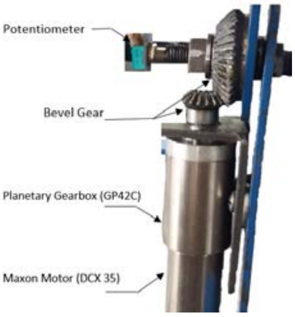

Fig.15 articulation components

The electronic circuit consists of an arduino mega 2560 board control two Dual module H-Bridge DC MOSFET IRF3205, four potentiometer used to sense the articulation rotation angles. Four Ultrasonic sensors used to detect the patient intention, and two FSR sensor are implement to detect the presence of foot on the ground fig 16.

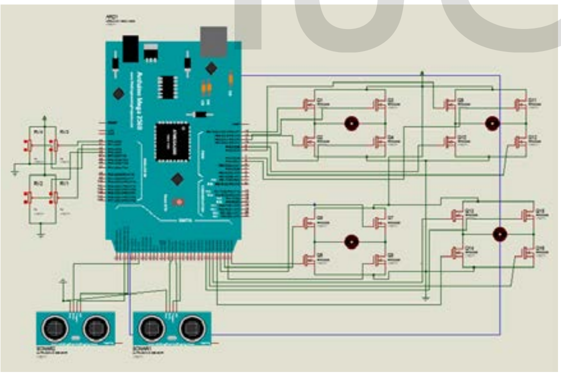

Fig.16: exoskeleton's electronic circuit

4. CONTROL STRATEGY:

The main task of the controller is to generate the required motor voltage to reach the desired angle at a defined velocity and torque. To ensure normal gait, each joint requires several variations in velocity and torque depending on the angle to reach on the knees and on the hips. To define this variation a dynamic modeling is required to determine the equation between angle, velocity, acceleration, torque and the voltage.

3.1 Dynamic modeling:

The dynamic modeling determines the equations between the torques applied by the actuators on the joints and the angles, speeds and accelerations of the exoskeleton. They are two dynamic model: The direct dynamic model and the inverse dynamic model. The inverse model describe the equations: $\tau=f(\theta,\dot{\theta},\ddot{\theta}2)$. A previous study in [20] provide the following equations:

$$\tau_1= b\ddot{\theta}_1+\frac{1}{2}m_2\left(\frac{L2^2}{2}\right)\ddot{\theta}_2 + m_2L_1L_2\ddot{\theta}_1\cos(\theta_2) + m_2L_1\frac{L2}{2}\ddot{\theta}_2 \cos(\theta_2) - m_2 L_1 L_2\dot{\theta}_1\dot{\theta}_2\sin(\theta_2) - m_2L_1\frac{L2}{2}\dot{\theta}_2^2\sin(\theta_2) - m_1g\frac{l1}{2}\sin(\theta_1) - m_2gL_1\sin(\theta_1) - m_2g\frac{L2}{2}\sin(\theta_1+\theta_2) \tag{1}$$

$$\tau_2 = m_2\left(\frac{L2}{2}\right)^2\ddot{\theta}_2+\frac{1}{2}m_2\left(\frac{L2^2}{2}\right)\ddot{\theta}_1 + m_2L_1\frac{L2}{2}\ddot{\theta}_1\cos(\theta_2) - m_2L_1\frac{L2}{2}\dot{\theta}_1\dot{\theta}_2\sin(\theta_2) + m_2L_1\frac{L2}{2}\dot{\theta}_1^2\dot{\theta}_2\sin(\theta_2) + m_2L_1\frac{L2}{2}\dot{\theta}_1\dot{\theta}_2^2\sin(\theta_2) - m_2g\frac{L2}{2}\dot{\theta}_2 sin(\theta_1+\theta_2) \tag{2}$$

$$b = m_1\left(\frac{L1}{2}\right)^2 + m_2(L_1)^2+ m_2\left(\frac{L2}{2}\right)^2$$

$\tau1$: hip torque
$\tau2$:knee torque
L1 : hip/knee length
L2 : knee/angle length
m1 : hip/knee mass
m2 : knee/angle mass
$\theta1$: hip angle
$\theta2$: knee angle
Or the power on the motor shaft Pu = η* Pa
And Pa = U*I
Or the power on the motor shaft $P_u = \eta * P_a$

And P_a = U*I

In addition: $$\tau = \frac{Pu}{\dot{\theta}} = \frac{\eta * U*I}{\dot{\theta}} \tag{3}$$

$$U=\frac{\tau}{\eta*I} * \dot{\theta} \tag{4}$$

η: motor efficiency
Pu : useful power
Pa: total electrical power
U: motor voltage
τ : Motor torque

The equations Eq.1, Eq.2 and Eq.4 determines the motor voltage for a defined joint angle, velocity, acceleration and torque.

3.2 Matlab simulation:

The figure 17 illustrate the Block diagram of the PID closed loop control system developed for the exoskeleton:

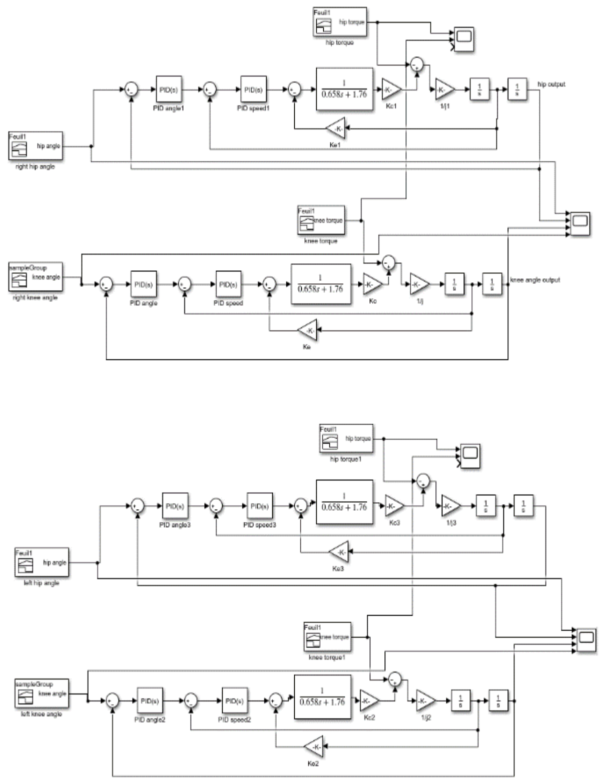

Fig.17 Exoskeleton Block diagram PID control system

Using simulink in matlab, the simulation showed the following results:

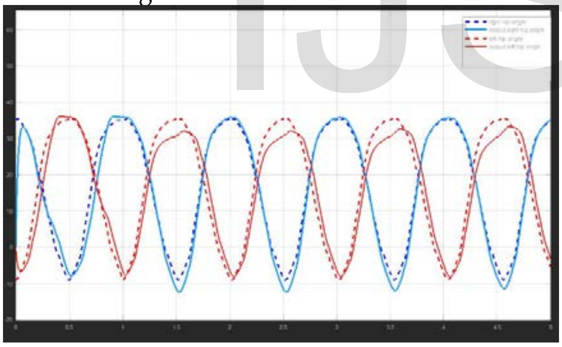

Fig.18 Input and output of right hip angle and left hip angle during the gait: kp=1.5 ki=0.1, kd=1: speed constant, torque constant. biomechanical data extracted from [21].

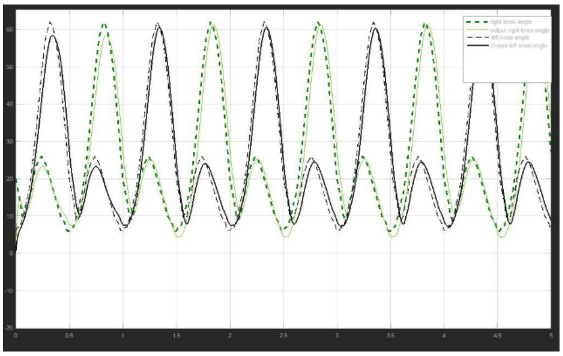

Fig.19 Input and output of right knee angle and left knee angle during the gait: kp=1.5 ki=0.1, kd=1: speed constant, torque constant.

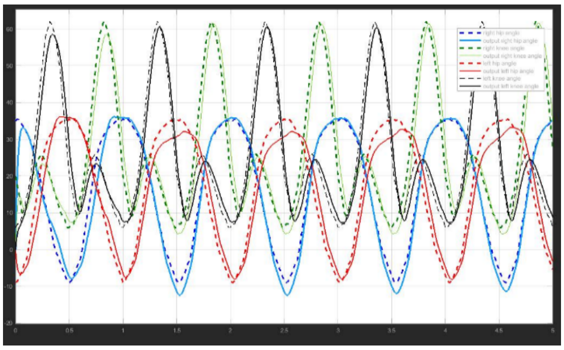

Fig.20 Input and output of joint angle during the gait: kp=1.5 ki=0.1, kd=1: speed constant, torque constant. Biomechanical data extracted from [21]

3.3 Human machine interface:

Many HMI are already developed for exoskeletons systems [22], the common method is to use buttons or graphical user interface GUI to control the exoskeleton motion (fig.21) (fig.22). In the present work, we tend use a novel human machine interface (HMI) facilitate the control of the exoskeleton without the involvement of the paraplegic children. Two Force resistor sensor (FSR) mounted beneath the crutches, and four ultrasonic sensors implemented on the exoskeleton, two on the feet, and two on the crutches (fig.23). During STS transition, the FSR sense an immense force applied on the crutches, this signal transferred to the microcontroller using Bluetooth transmitter, the microcontroller control the motors to generate the stand motion, and that push the patient to stand.

However, the patient move the crutch to start the walk, the ultrasonic sensors installed on the crutches and the feet detect a variation in distance (du, df) between the leg and crutch, which mean the intention of patient to walk. The ATmega microcontroller controls the motors to generate the gait sequence. This method allows the patient to begin the gait with the right or left leg. If the patient moves the right crutch, the microcontroller moves the right leg, and if the patient moves the left crutch, the microcontroller generates the walking movement on the left leg.

Fig.21 Exoskeleton CUHK HMI

Fig.22 Exoskeleton REWALK HMI

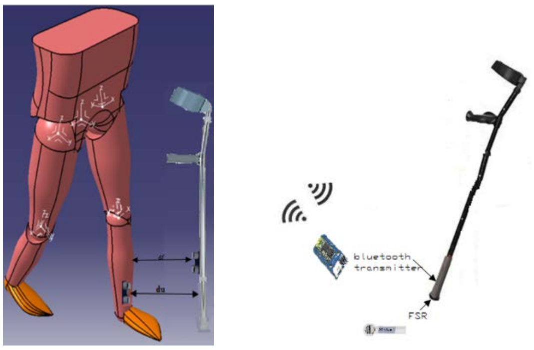

Fig.23 Exoskeleton NOD-P HMI

3.4 Discussion

The Figure 18, 19 and 20 illustrate the performance of the PID closed-loop controller. The control system could track and follow the desired input angles on the knee and hip. An error still occurs between desired angles and obtained angles. This performance obtained for a constant speed walking, this means that we did not discuss the PID performance for variable speed walking.

The human machine interface designed to control the robotic device without children involvement. In fact, the children can make erroneous manipulations that affect the normal functioning of the exoskeleton, for this reason we remove any buttons or android interface and we adopt a self-control system that allows the exoskeleton to predict the patient's intuition using only the movements of the crutches.

5. CONCLUSION AND FUTURE WORK

The current work present an Exoskeleton robotic device named NOD-P assist children with spinal cord injury recovering gait, The entire system, including the mechatronic structure, electronic circuit, control system and human machine interface was designed to be simple and to reach the minimum price considering efficacy, ergonomics, lightweight and comfort. The prototype already manufactured in Ibn Tofail University with a budget of 100 USD.

Clinical studies involving a larger cohort of paraplegic children required to indicate the performance of the device in the daily life of paralyzed children. Furthermore, studies should be focus on the safety of the wearers, since the children are wearing powered devices and they could not counteract any dysfunction of the exoskeleton.

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