Developing An Exoskeleton-Wheelchair Designed For Tetraplegic Patients

Elouarzi Abdelkarim, Sedra Moulay Brahim

Abstract: This article presents a wheelchair-exoskeleton system designed for individuals with tetraplegia. The system purposes to help patients who suffer total body paralysis due to complete spinal cord injury in the cervical segments. A mechatronic system is proposed in order to establish a secure and stable gait for disabled patient. A proposal of voice control strategy is also presented as a part of the human-machine interaction due to the inability of the tetraplegic patient to move the parts below their neck. These systems open the way to new researches for robotic solutions intended to improve the life quality of high-level spinal cord-injured patients.

Keywords: Exoskeleton, Tetraplegia, Quadriplegia, Wearable Robotics, rehabilitation, Embedded System, handicap, disabled treatment.

I. INTRODUCTION

The term Tetraplegia refers to impairment or loss of motor and sensory function in the cervical segments of the spinal cord due to damage of neural elements within the spinal canal. Tetraplegia results in impairment of function in the arms as well as typically in the trunk, legs and pelvic organs, including the four extremities. It does not include brachial plexus lesions or injury to peripheral nerves outside the neural canal. [1]. The reasons for such situation can be different: traffic accidents, gunshot injuries, knife injuries, falls, sports injuries, stroke, arthritis, high blood pressure, degenerative diseases of bones and joints and cases of paralysis and birth defects. This situation decrease intensively the mobility of the patient and causes many dangerous complications: slough, Muscle stiffness, urinary disease…etc. moreover, the patient suffers psychological issues due to their inability to exercise daily tasks and people's behavior around him. The patients with such severe disabilities are not able to perform their everyday actions, such as: feeding, toilette usage and movement through space. Depending on the severity of the disability, a patient can retain freedom of movement to a certain level by using different medical devices [2]. Many researches in medical field are oriented to facilitate the tetraplegic life like stem cell transplantation, bone marrow transplant. However, their result are still far from the desired. An alternative solution appears in the last decade to aid the disable patients to regain the mobility: the powered wearable exoskeletons suit. Many projects of robotic exoskeletons are already developed, table 1 shows a summary of some exoskeletons systems already available in the market. However, all those designs are oriented to paraplegic people.

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Otherwise, the tetraplegic people can use the exoskeleton to improve their health, and to avoid many side effects, but the actual solutions are based on using the arm to maintain the stability, that is an obstacle for the individuals with tetraplegia, the tetraplegic patient cannot use their hand to maintain the stability of the exoskeleton suit.

Table 1: *summary of wearable exoskeletons systems*

exoskeleton	Company/ university	Country	Price (USD)
HAL	Cyberdyne	japon	650 / month
Ekso bionics		USA	110 000
Rewalk	Argo Medical	israél	50 000
Indego	Vanderbilt university	USA	130 000
Phoenix	SuitX	USA	45 000
Exoatlet	ExoAtlet	RUSSIE	53 000
ATLAS 2030	Marsi Bionics	SPAIN	50,000
2WA-EXO	ITRI	Taiwan	----------
LOKOMAT			100 000
Exo-H3	Technaid	Spain	70 000
CUHK-EXO	UCHK	Hong Kong	25 000

The following work present a powered stand-up wheelchair with an exoskeleton named NOD-T, controlled by the voice, designed for the tetraplegic patients. In the first section, we describe the mechatronic design of the developed exoskeleton, in the second section, we present the algorithms and the control system employed for the developed prototype. In the third section, we present an analysis and the limitation of the system.

II. Mechatronic construction

a) mechanical design

The target function of the proposed system is to provide an alternative solution for the tetraplegic patient to stand-up and to walk easily. The mechanical design must to be safe in case of a sudden failure, self-stable, modular, lightweight, simple structure, easy to use at home, in the office, in the school and in the street. The developed prototype is represented in Fig.1, Fig.2, Fig.3, and Fig.4.

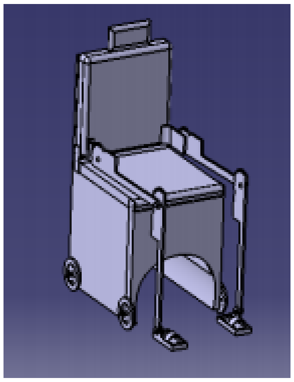
Fig.1

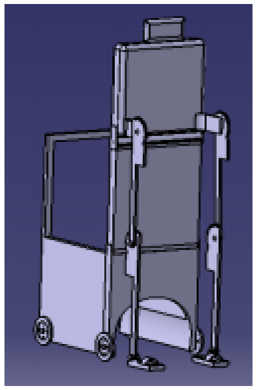
Fig.2

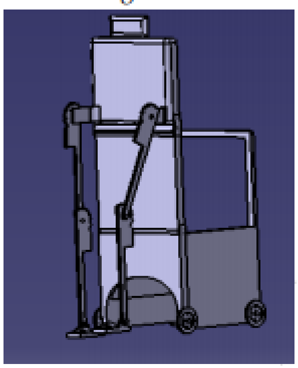
Fig.3

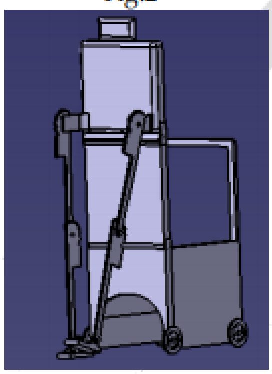
Fig.4

The present system is composed of an electrical stand-up wheelchair connected to a powered orthosis. The electric wheelchair has a pair of motorized wheel ensure the mobility and the rotation of the system in the sagittal and frontal plane. In addition, two linear actuator 24v (Linak LA35) provides the standing function. The powered orthosis (fig.5 and fig.6) consist of two motors on the hips, and two others on the knees.

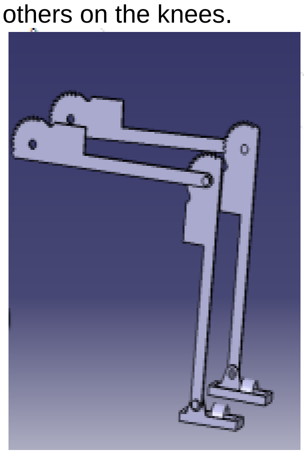
Fig.5

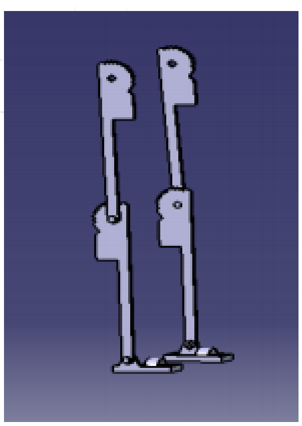
Fig.6

The DC gear-motor joined to a small gear G1, this gear transmit the rotational motion to a train gear G2 (fig.8) that transmit the motion to the support S (fig.7)attached to the patient. [3] This orthosis ensure the walking task of the tetraplegic patient.

Fig.7

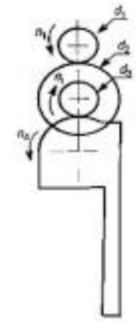
Fig.8

b) electronic system:
The NOD-T is developed for tetraplegic patients who lose the motor and sensory functions in their lower limbs and hands. The patient find a difficulty to use their hand or finger to control an electronic circuit. Some research use EMG sensor to help SCI patients to control exoskeleton system, others use Brain interface as HMI. In the present work, we use a voice human interface to control the system. The electronic circuit composed of 4 dual-channel H bridge module and an Arduino Mega 2560 microcontroller board. A flex sensor used in each joints to calculate the angles, the velocities and the acceleration in each articulation.

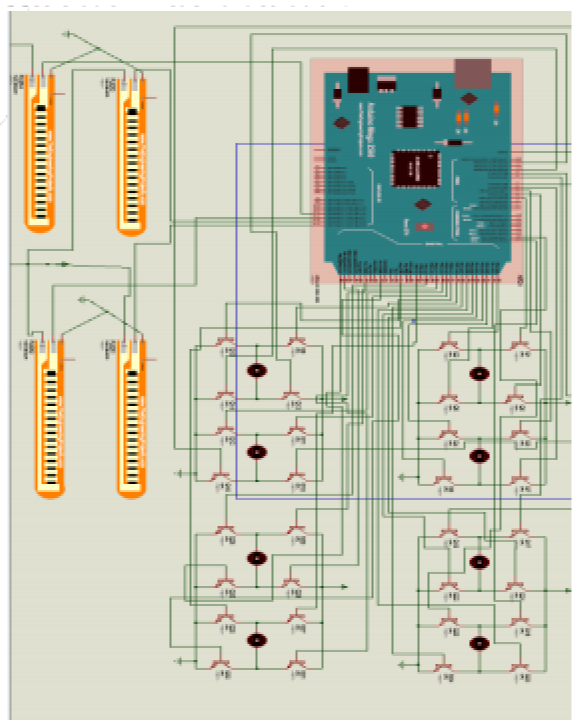
Fig.9

III. Control strategy:
The control of wearable exoskeleton robot is a complicated issue, due to the existence of many factors. This becomes more difficult for a stand-up wheelchair exoskeleton because the motion of the exoskeleton joints must to be in harmony with the motion of the wheelchair actuators. The advantage of the designed system that the system is naturally stable, the tetraplegic patient will not fall when

standing or moving and this make the task of control more safe. Many control strategies designed for the exoskeleton system, Y.Wen introduce neural PD and PID controls for Exoskeleton Robots [4]. J.Wu, J.Huang and Y.Wang implement a fuzzy PID controller for the wearable rehabilitation robotic [5]. G.A.Ollinger and J.E.Colgate proposed an Active-Impedance control for lower-limb assistive exoskeleton [6]. K.Kiguchi, T.Tanaka and T.Fukuda introduce neuro-fuzzy control for the wearable exoskeleton [7]. L. Wang, E. H. Van Asseldonk and H. V.Kooij developed a Model Predictive Control for the exoskeleton system [8]. M.Khadiv and A.Herzog present Walking Control Based on Step Timing Adaptation for humanoid Robots [9]. N.Aphiratsakun and M.Parnichkun use the zero moment point (ZMP) concept for balancing control of the exoskeleton-I (ALEX-I) [10]. C.Carignan, J.Tang, and St.Roderick utilized the admittance controller for the MGA exoskeleton In the proposed system, we propose a novel strategy of control base on mathematics equation between the exoskeleton joints angles and the wheelchair actuator parameters.

a) Position Analysis of the Exoskeleton

The joints Coordinates of the system is shown in figure. To calculate position of hip, knee and ankle, The Denavit-Hartenberg method is used. From the figure 5, the parameter for Denavit-Hartenberg equation must be specified due to reference coordinate.

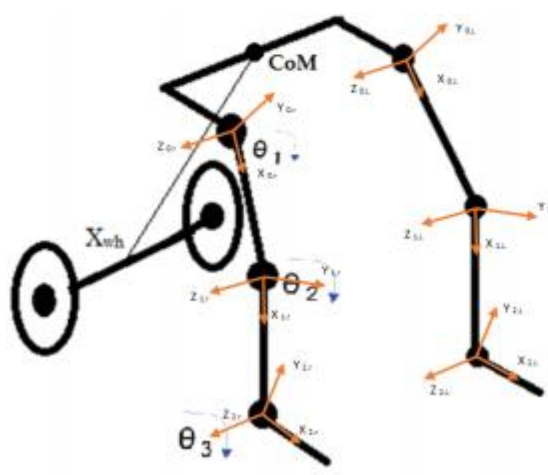

Fig.10 *joints Coordinates the wheelchair exoskeleton*

With the DH parameters in Table 1, the transformation matrix from the (i-1)th to ith frame may be obtained as:

$$^{i-1}T_i = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & \sin\alpha_i \sin\theta_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cos\theta_i & -\sin\alpha_i \cos\theta_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

θ_i Joint angle
α_i Link twist
d_i Link offset
The transformation matrix from the i^{th} link to the base link 0 calculated using the equation:

$$^0T_i = {}^0T_1 \times {}^1T_2 \times {}^2T_3 \times \ldots \times {}^{i-1}T_i$$

The transformation matrix of the end frame relative to the base frame:

$$^0T_3 = \begin{bmatrix} \cos(\theta_1+\theta_2+\theta_3) & -\sin(\theta_1+\theta_2+\theta_3) & 0 & a_1\cos(\theta_1)+a_2\cos(\theta_1+\theta_2)+a_3\cos(\theta_1+\theta_2+\theta_3) \\ \sin(\theta_1+\theta_2+\theta_3) & \cos(\theta_1+\theta_2+\theta_3) & 0 & a_1\sin(\theta_1)+a_2\sin(\theta_1+\theta_2)+a_3\sin(\theta_1+\theta_2+\theta_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The forth column of matrix **T** represents the position of the third link of the limb.

$$x = a_1\cos(\theta_1) + a_2\cos(\theta_1+\theta_2) + a_3\cos(\theta_1+\theta_2+\theta_3)$$
$$y = a_1\sin(\theta_1) + a_2\sin(\theta_1+\theta_2) + a_3\sin(\theta_1+\theta_2+\theta_3)$$

b) Sit to Stand transition control:

Standing is an important action of daily life. That allows persons to execute many regular and usual task, such as cooking, working, reaching and gathering object …etc. For tetraplegic patient, standing with the assistance of a standing wheelchair helps to increase functional independence and improves an individual's physical and psychological well-being [11]. In fact, standing improve some physical parameters such as, Bone Mineral Density (BMD), respiratory system function, cardiovascular system function, skin integrity, and joints range of motion. In addition, standing has positive effects on bowel regularity, and it decreased the number of urinary tract infections [12]. In the studied system, the standing function is provided by linear actuator installed on the wheelchair and gear motor on the hip and the knee of the exoskeleton. During the stand-up, the rotation of the exoskeleton motors and the linear motion of linak actuator must be synchronized. For this reason, we use two Flex sensor in knee articulation, one on the wheelchair, and the second on the exoskeleton knee. The wheelchair flex sensor provide the angle variation on the wheelchair knee axe, which allows the microcontroller to calculate the rotation speed of the wheelchair Ωw ,the following algorithm shows the procedure adopted to calculate Ωw:

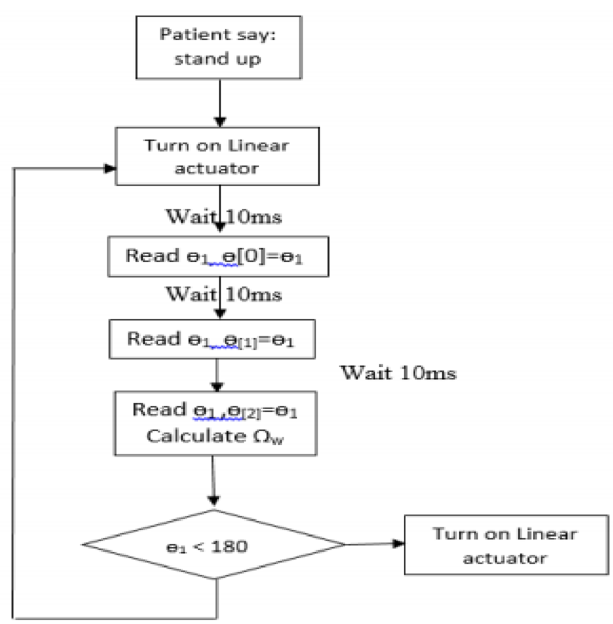

Fig.11 *the implemented algorithm to calculate the wheelchair rotation speed*

The previous algorithm provide the input speed to a closed Loop PID rotation speed controller Fig.12. This system provide the suitable voltage to the exoskeleton motors to ensure the same rotation speed on the exoskeleton articulations.

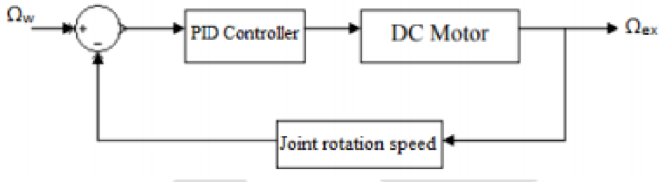

Fig.12 *speed control for exoskeleton motors*

c) Walking Control Design:

The walking control system that we propose allows the user to give two commands: "walk" and "stop". The exoskeleton motion and the rotation of the powered-wheels of the wheelchair must be coherent, two ultrasonic sensors and two FSR (Force-Sensing Resistor) ensure this requirement, one sensor each side (fig.13). Three phases constitute the gait cycle. The first phase begins when the patient's command "walks", the system in the standing position, the ultrasonic sensor provide the actual position of the right leg (dustart), the right leg of the exoskeleton take the first step tracking the angle of the hip and the knee angle in Figure 14. Once the FSR sense the presence of foot on the ground, and the ultrasonic sensor detects that the distance is greater than 200 mm, the first phase finished, the ultrasonic sensor deliver the new position of the right leg (duend) to the arduino board, that allows the microcontroller to calculate the step speed Ws=(duend- dustart) / time. The second phase commence, the left limb of the orthosis proceed the gait following the angle of the hip and the knee angle in Figure 14. Once the left leg begin walking, the powered wheels turn on and move the wheelchair forward until the right ultrasonic sensor sense that the wheelchair reach dumin , the electrical wheels turn off, and the left leg of the exoskeleton continue the step until the left FSR sense the presence of foot on the ground. The speed of the wheelchair is the same speed Ws computed in the first phase. The third stage begins when the patient's command "Stop", the exoskeleton returns to stand position, if the right leg on the front, the exoskeleton move the left limb and the wheelchair until duright = duleft. In this phase, the patient can return to the sitting position.

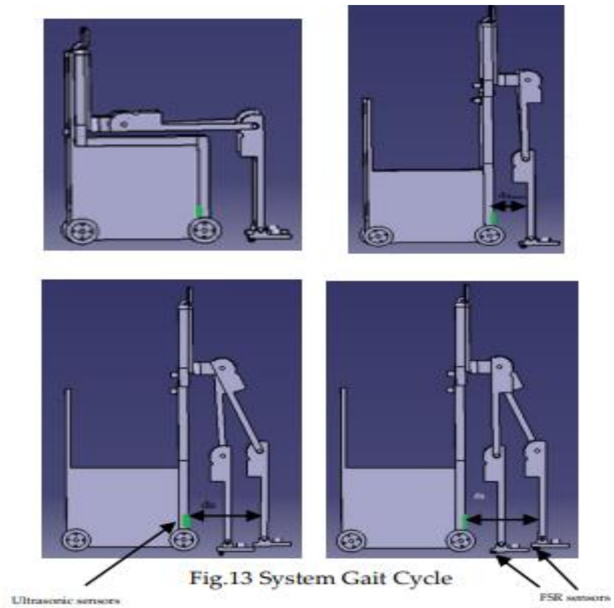

Fig.13 System Gait Cycle

dumin :distance between wheelchair and the right limb

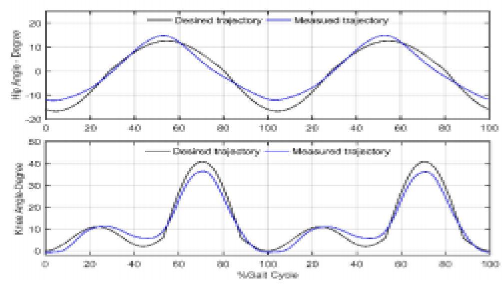

Figure 14. *The revolute angle of hip and knee joints, the gait data is normalized and plotted as reference trajectories [13]*

The following algorithm describe the walking motion:

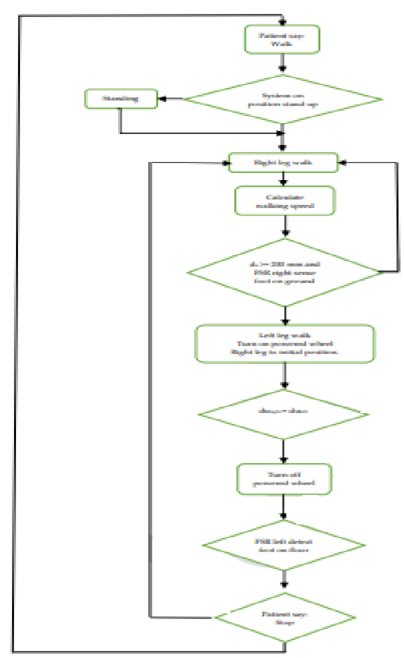

Fig.15 *the implemented algorithm for walking function*

IV. Analysis and discussion:

Global statistics shows an increase in the numbers of individuals suffering from Spinal cord injury (SCI), Fig.16 shows the huge percentage of people with tetraplegic in the international map of SCI from traumatic causes. Robotic devices can assist them in the active rehabilitation to stand and walk. In this work, we purpose to develop a robotic device named NOD-T help tetraplegic patients to regain the mobility. The mechanical structure devised to be safe and stable, HMI also designed to be easy in use for patients unable to move the parts underneath their neck, and a control approach implemented to ensure the harmony of the system during the gait cycle. The control system designed considering the linear movement of CoM (centre of mass). In fact, the CoM has a nonlinear displacement (fig.17), which result an assistive walk of the system dissimilar that the normal gait. this difference does not affect the efficiency of the system.

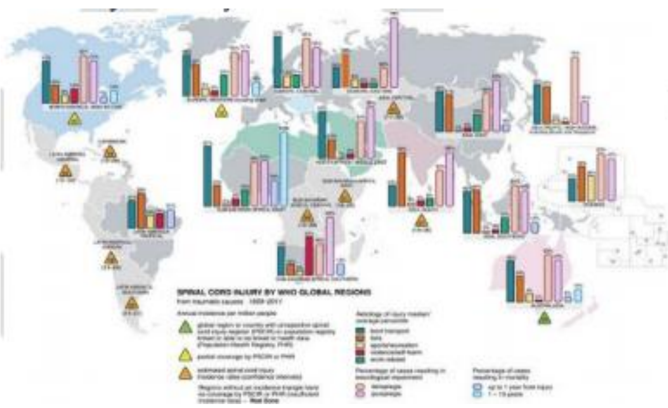

Fig.16 *Spinal cord injury by WHO Global Regions from traumatic causes 1959–2011 [14]*

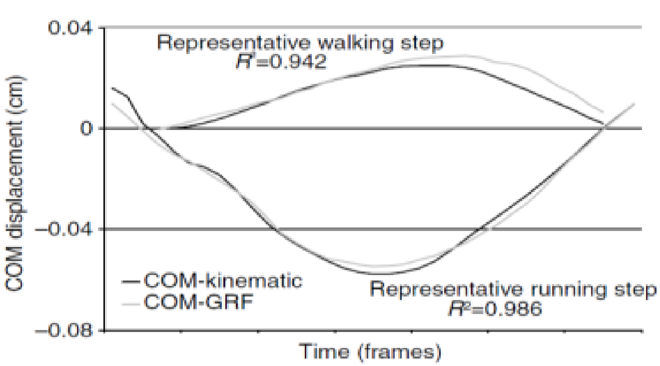

Fig.17 *vertical displacement of the CoM by ground reaction forces (GRF) and kinematically [15]*

Conclusion:

The presented work introduces the idea and design of an exoskeleton-wheelchair for tetraplegic patients controlled via the voice. This robotic device help the tetraplegic subjects to stand and walk on a flat ground. This system can be also used for paraplegic patient in the first period in rehabilitation center as training device before use the wearable exoskeleton suit. The limitation of this study is that, the actual design is unable to climb stairs. In future work, we will study a novel design of wheelchair-exoskeleton able to climb the stairs and walk on a rough terrain, and we will improve the performance of gait cycle using a novel control system in which the CoM has a nonlinear movement, this novel control system can improve the gait comfort. Therefore, we also plan to use the NOD-T as part of a training protocol for tetraplegia patients in rehabilitation center.

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