Reducing electrical energy consumption for a child wearable exoskeleton suit using a new mechanical design

Elouarzi Abdelkarim, Sedra Moulay Brahim

Abstract: This study explores the feasibility of a novel mechatronic structure for exoskeleton child system designed to facilitate standing, walking, and stair climbing of paraplegic children, this design based on an actuated hip and passive knee. The main objective of this design is reduce the electrical energy consumption and increase the batteries charge time. A solenoid used to maintain the standing of the exoskeleton and control the motion of the knee joint and algorithm implemented to control the total motion of mechanical structure. In the First portion, the mechatronic design presented and detailed through the mechanical design and electronic circuit. Second, the control algorithm presented including the algorithm of control and the interactive human machine interface. Finally, a simulation in Matlab presented to conclude and approve the energy reduction of the mechanical design.

Keywords: Exoskeleton suit, paraplegic child, Wearable Robotics, rehabilitation, Embedded System, handicap, disability.

I. INTRODUCTION

Childhood is a very sensitive stage in human life. It is a period of honing personalities, improving skills, developing basic knowledge and building human culture. In fact, the school is the perfect environment allows the child to growing up and learning. Otherwise, lacking of accessibilities denied the paraplegic children to access the classroom. In morocco, large number of schools miss accessibilities for paraplegic children [1]. This situation leads a huge number of children to leave the education, and growing in ignorance and illiteracy, according to the national rapport of handicap in Morocco [2], the government counts only 41% of disable children in private and public schools. Despite the government efforts, increasing the number of paraplegic child attending school is very difficult objective, other factors involve the children schooling like absence of public transport for disable person, parental availability to escort their children…etc. Furthermore, disability has a deep impact on the physical and psychological development of children required continuous medical monitoring that avoids physical and psychological complications.

The current technology reveal a new solution that can assists the paraplegic child to overcome their disability: the wearable exoskeleton suit. A robotic device helps the disabled patient get up, stand, walk and climb the stairs. In fact, it is not a new invention, the first version created by Sir Symon in 1830 and the first patent dating from 1889 in Russia [3]. This device has been hibernated for more than a century before a new version was unveiled in 1960 in the United States. Over the last decade, multiple exoskeleton solutions have been developed for use in the medical, industrial and military fields. Compared with traditional assistance methods such as manual and electrical wheelchairs, which can move only on a plane surfaces, lower limb exoskeletons help paraplegic children to move on any surface such as forest, beach, rough terrain and stairs. Furthermore, from a psychological perspective, they can help strengthen the self-confidence, the volition, and the feeling of independence of paraplegic child [4].

Most exoskeletons structure use an actuator for each joint (generally a flat maxon DC motor with harmonic drive gearbox), three actuator for each leg, which causes a massive electrical consumption of the batteries. This paper present a mechanical design for exoskeleton suit developed to ensure the gait motion using only one motor for each leg. This strategy aim to reduce the power consumption and make the exoskeleton lighter on maintaining the exact function of the exoskeleton. In the next Section, the mechatronic design, including the mechanical structure, electronic circuit and sensor specifications presented. In Section 3, the control strategy and the algorithm for the entire system presented and tested using Matlab. In Section 4, an analysis and discussion of the result will be described. Finally, Section 5 concludes the paper.

II. MECHATRONIC DESIGN

The current lower limb exoskeleton (NODP-v2) has been developed not only for rehabilitation training but also to be in use for walking at home, in school, in street, climbing stairs, playing

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soccer…etc. The main purpose is to assists children with disabilities lives a normal life, walk independently to school, climb stairs and play with other children. For this reason, the mechanical design must be ultra-thin and lightweight. The weight is a challenge for all the designs of the exoskeleton wearable robot, the lighter the exoskeleton is, the greater the comfort of the child during the gait (fig.1). The stability still a major defy, for this version we maintain the stability using two crutches, a next version planned to remove the crutch and develop a new prototype NOD-Pv3 with self-stable mechanism.

The developed system displays an incorporation and interdependence of mechanical design, electronic circuit, sensors network, control engineering, embedded programing and user interface. The hip joint consists of a DC maxon motor (DCX 35 L Ø35 mm, Graphite Brushes), and planetary gearbox (GP42C 156: 1). Bevel gears (Module 1.5, 16 teeth / 32 teeth) convert the direction of movement between axes. A potentiometer placed into the articular axis to capture the variation of the angle of rotation of the hip.

The design of the knee joint is the principal point in the functioning of the exoskeleton, many passive and active knee exoskeleton already designed, NOD-Pv2 use a novel passive knee design.

the knee joint consist of a mechanical structure illustrated in fig.2, it is composed of a cam form and a solenoid connected to a 5V DC relay controlled by the arduino Uno. The support contains three rotation limits, the first limit to maintain the standing position, the second to limit the rotation of the knee during the gait, and the third to limit the rotation during the stand to sit motion. The electronic circuit (fig.4) consists of an arduino Uno board control a 50A dual-channel motor drive module. One Ultrasonic sensor used to detect the patient intention, and two FSR sensor are implement to detect the presence of foot on the ground fig 2. The exoskeleton's mechanical design comprises legs ties, motors, gearbox, a pelvic girdle, lithium ion battery, electronic circuit. The total mass of the exoskeleton is 15.5 kg. That make it one of the lightweight exoskeleton system known.

Dual spiral spring (fig.3) placed into the knee axis stores the mechanical energy during the Stand to sit position; this energy helps the paraplegic children to stand up that reduce the physical effort needed from the child to standup. In addition, during the gait, in the flexion phase the spiral stores the energy that be released for the extension phase. This energy calculated using the following equation:

$$E = 0.5 \times Ks \times \theta^2 + 0.5 \times F \times x \quad (1)$$

Ks: spiral spring stiffness
Θ: angle of the knee
F: force applied on the cord
X: tendon cord elongation

Exoskeleton	Weight
ReWalk [5]	23.3 kg
Hal [6]	22 kg
Exoatlet [7]	20 kg
Indigo [8]	12kg
Wandercraft [9]	60kg

Fig.1 table weight

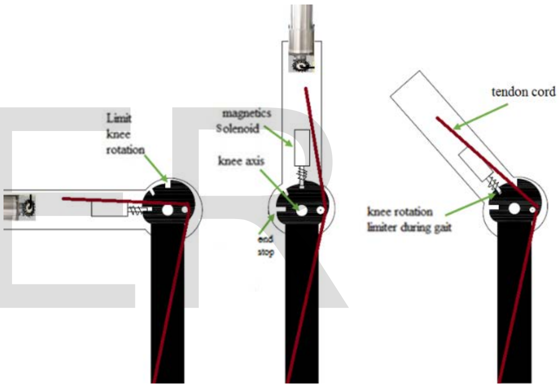

Fig.2 Mechanical structure

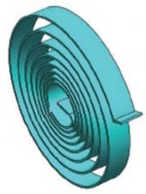

Fig.3 spiral spring

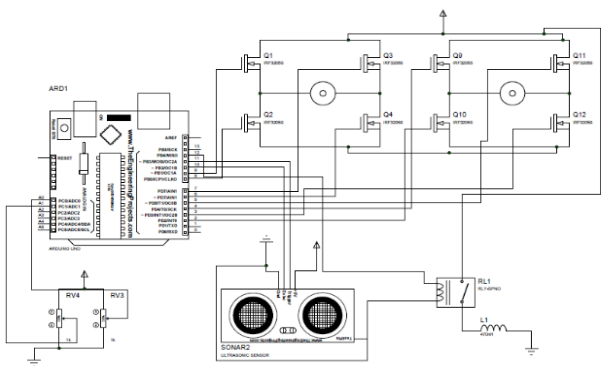

Fig.4 Electronic circuit of the exoskeleton

III. CONTROL SYSTEM :

The principal factors to take on consideration for the exoskeleton control system is how to reach the optimal control performances of the mechanical structure. However, generate the optimal gait trajectory, reduce the power consumption, guarantee a suitable human machine interface (HMI), and ensure the stability and the security of the paraplegic patient. The first objective requires the ability to track the variation of the angle of the hip and knee shown on the graph of (fig.5) and (fig.6). Impedance and admittance controllers (fig.7) are a trivial choice to control the exoskeleton actuators. This is because this controller provide a relation between torque and angle [10]. The impedance Z defined on the following equation:

$$Z = \frac{\tau}{\theta} \quad (2)$$

- θ Joint angle
- **τ joint torque**

Other control systems also developed to optimize the path trajectory of the exoskeleton: adaptive PID controller (fig8) [11] [12], predictive PID controller [13], self-tuning PID controller [14] …etc. In this work, a PI controller implemented as arduino program to control the angle positions of the motors on the hip. to generate the gait trajectories, the step is divided on one hundred parts on time, each part of time equal 6ms, the cadence of child gait estimated on 90 step/min, the PI controller are adjusted to attain the required angle each 6ms.

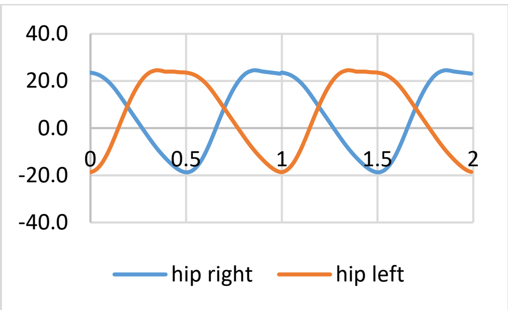

Fig.5 variation of hip angle during the gait

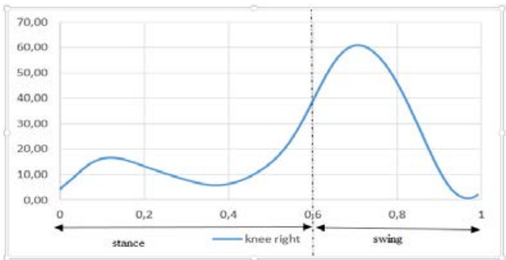

Fig.6 variation of knee angle during the Phases of the normal gait cycle

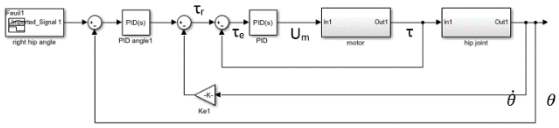

Fig.7 Impedance control diagram

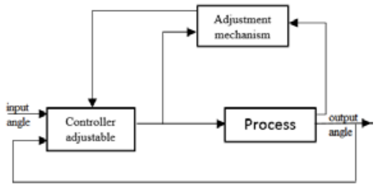

Fig.8 block diagram of adaptive control

1. NOD-PV2 algorithm control

In the stand to sit transition, the microcontroller activates the solenoid, an electric current passes through the coils windings, it acts like an electromagnet and the plunger pushed inside the coil that unlock the knee joint and allows the rotation of the knee in the anti-clockwise. In fact, the knee rotation is limited using end stops, and the knee articulation cannot turn outside these borders (fig.2). In this phase, a Potential energy stored by the spiral spring and the tendon cord, this energy released as a mechanical power in the sit to stand transition that helps the children to standup.

In the sit to stand transition, the microcontroller activates the solenoid, the child uses his hands and the released energy restored from the spiral spring and the elastic tendon cord to stand, at the standing position, the microcontroller turn off the solenoid, the plunger pushed inside the groove, locking the knee mechanism and maintaining the stand position.

On the other hand, the gait cycle, (Fig. 9) is divided into the stance and swing phase. The stance phase constitutes 60% of the cycle and it 'is subdivided into five phases: heel strike, loading response, mid-stance, terminal stance and pre-swing. The swing phase takes up about 40% of the gait cycle and is subdivided into 3 phases: toe-off, mid-swing and terminal swing, [15], [16].

During the heel strike and loading response the microcontroller lock the knee joint mechanism preventing the knee from buckling, and activate the rotation of the hip on the clockwise and anti-clockwise to move the leg forward until the foot is making contact with the ground. In this point, the microcontroller unlock the knee joint mechanism to allow the flexion of the knee during the pre-swing phase, once the knee flexion attain the limit walk angle, the microcontroller lock the knee. Throughout this phase the spiral spring and tendon cord store the mechanical energy. During the toe-off and mid-swing phases, the microcontroller unlock the knee system, the spiral spring and tendon cord release the mechanical energy stored in the previous phases to generate the extension of the knee, and rotate the hip joint in anti-clockwise. In the last phase, the microcontroller lock the knee mechanism and activate the rotation of the hip on the clockwise to push the body forward. This sequence control the knee and the hip joints, which generate the gait cycle.

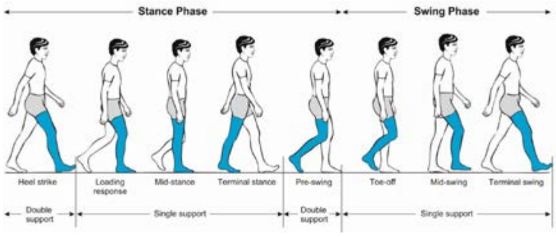

Fig.9 Phases of the normal gait cycle [17]

2. Human machine interface

This exoskeleton is developed for children to walk in the school, in the street, at home without parental escort, using boutons or graphical interface can causes false manipulation, for this reason we adopted a self-learning method to predict the children intuition using crutch and ultrasonic sensors (Fig.10). In the sit to stand transition, the child move the crutch twice forward and stop, the ultrasonic sensor detect a twice variation of the distance between the legs and the crutches, this motion mean the desire of children to stand. The microcontroller control the motors and the solenoid to generate the standing transition. Otherwise, to walk, the children move the right crutch forward. The ultrasonic sensor detect a variation of distance between the right leg and the crutch, the microcontroller move the left foot forward, in the next phase, the child move the left crutch, the microcontroller detect a variation of distance between the left leg and the left crutch, the microcontroller move the right foot, and the cycle repeats. To sit, the child move the right crutch twice back, the microcontroller detect this variation, and control the exoskeleton to sit. This simple method allows the control of the exoskeleton motion without any involvement of child and avoid any bad use of the device by patient.

Fig.10 Crutch-leg Distance detection

3. Matlab simulation

The following figure show the Block diagram of the PI control system implemented to control the DC motors on the hips:

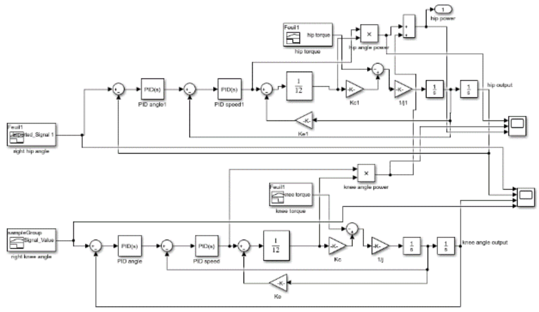

Fig. 11 Exoskeleton PI control system

The PI constants (Kp and Ti) are adjusted to reach the desired angle in a time period of less than 6ms (fig.12). The simulation on Matlab shown the following results:

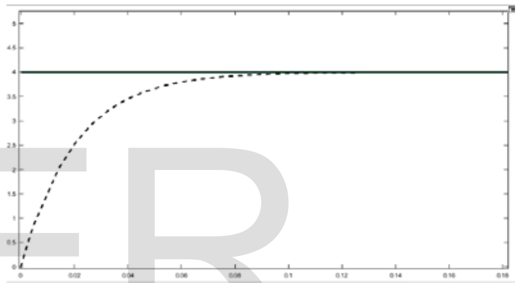

Fig.12 hip angle output of the control system for an input variation 4 degrees

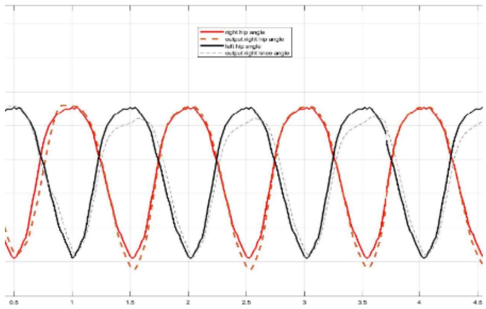

Fig.13 hip angle output: angle kp= 10 ki= 0.25: constant speed, with torque variation

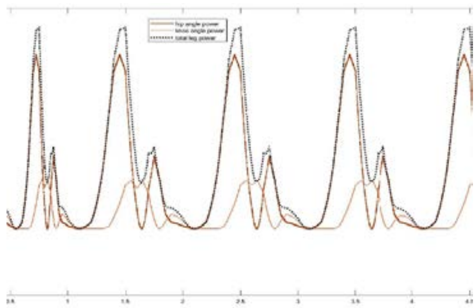

Fig.14 knee and hip motor energy consumption

IV. Result discussion :

The figure 13 represents the results of the hip angles variation for various torque applied on the exoskeleton. The graph shows the ability of PI controller to track a sequence of angular position on the hip constitute the normal gait cycle. In fact, the step is subdivided into 100 samples; the sampling period is 6ms, the figure 12 shows the aptitude of the control system to reach 95% of the required angle in 6ms, the interval between samples varies between 0.5 to 4 degrees. A spiral spring and a tendon cord store a mechanical energy utilized to actuate the knee joint, the solenoid maintain the knee mechanism and assist to the control of knee joint to generate the gait cycle. The figure 14 shows the energy consumption for the motors on the hips and compare this energy with an exoskeleton actuated by two motors, one the hip and another motor on the knee. The graph shows a reduction of electrical power consumption at most 25%, this reduction increase the charge time battery and allows the children to use the exoskeleton longer without charging. Overall using NODP-v2, the patient was capable to produce a valid gait pattern with minimal batteries energy. The comparison with a widely studied paradigm showed that our prototype had the potential to generate a gait pattern cycle closer to the normal walk. The proposed human-machine interface (HMI) addressed the problem of intention detection and prevented the misuse of the assistive devices by disabled children.

V. Conclusion :

This article presents the mechatronics design and the control strategy of a wearable lower limb exoskeleton developed to helps paraplegic's children in daily life. The NODP-v2 exoskeleton equipped with compliant elastic actuators is able to assist child with disabilities to walk using crutches to maintain the patient stability. This version reduces the mechanical energy and electrical power consumption that increases the batteries using time. Moreover, this mechanical structure is lighter, and can be worn under clothes. In addition, an interactive human machine interface implemented to allow the children controlling the device safely.

More work needed to improve the gait stability and allows paraplegics children to walk without crutches. Auto-correction trajectory gait and adaptive control system making auto-adjustment to the control strategy desired to improve the system's gait pattern.

Conflict of Interest

Elouarzi Abdelkarim and Sedra Moulay Brahim declare that they has no conflict of interest.

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