Mechanical Design and Control of an Active Wrist Orthosis

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***Abstract*—Lateral Epicondylitis and Medial Epicondylitis are occupational illnesses and they are frequently seen on people who are making excessive extension and flexion wrist movements more than 2 hours a day. Patients have to give a break in the middle of their working process because of the pain at the elbow location while performing extension and flexion wrist movements against resistive forces. To deal with this occupational disease, an active wrist orthosis device is designed first, and then, its successful operational functionality is shown in MATLAB/Simmechanics environment using a fuzzy logic controller.**

***Index Terms*—active wrist orthosis, fuzzy logic controller, EMG Signal Processing**

I. Introduction

Lateral Epicondylitis, or “tennis elbow” is a common musculoskeletal disease defined as being an inflammation or a tendon torn at elbow location called lateral epicondyle [1]. The ones who should perform repetitive extension wrist movements more than 2 hours a day due their occupation will probably get sick from this painful disease. The prevalence of the lateral epicondylitis was reported about 1.3% for the 45-54 age range in the society [2]. Medial Epicondylitis is another wrist disease which is occurred due to making excessive flexion wrist movements. It is impossible to continue daily wrist activities due to pain in the later stages of the diseases. This study aims design and control of an active wrist orthosis (AWO) which would be used to assist the extension and flexion wrist movements for the prevention or the treatment of the aforementioned diseases.

Orthoses are mainly used for the rehabilitation of patients who lose their limbs’ function completely or particularly. Active orthoses, which are also known as exoskeleton robots, interact with human limbs via EMG sensors so that the device user intention is always at the first place. The passive ones are generally used for the rehabilitation of the partially paralyzed patients in which only a predetermined motion profile is performed in a repetitive manner for the unfunctional limbs. For example, Ref. [3] had designed a stand-alone active orthosis for functional assessment of a wrist while making Flexion/Extension (F/E) and Radial Deviation/Ulnar Deviation (R/U) hand movements. IIT-Wrist is a 3-DOF (including Supination and Pronation besides F/E and R/U movements) wrist exoskeleton robot which was designed in order to provide kinesthetic feedback during the training of motor skills [4]. ExoRob is another electromechanical device which could be worn on the lateral side of the forearm and would be used for passive rehabilitation exercises of the F/E and the R/U wrist motions [5]. SUE is a 2-DOF pneumatically actuated robot for wrist rehabilitation after stroke [6]. DULEX II is a wearable hand rehabilitation robot capable of hand function assistance for stroke survivors [7]. WEP is a lightweight and wearable wrist exoskeleton prototype and has a 2-DOF which includes only F/E and R/U wrist movements. The F/E motion is provided by a linear actuator giving a 2.2 Nm assistive torque to the wrist with a very low velocity value which is about 10 °/s. Moreover, this device is controlled by the EMG sensors in order to estimate the intention of the user [8]. An EMG based control of a 3-DOF exoskeleton robot was developed to assist the wrist motion of physically weak individuals in their daily lives [9].

It is seen that there are a lot of wrist exoskeleton robot in the literature; but, none of them could be used for the avoidance or the treatment of the Lateral and Medial Epicondylitis diseases since an assistive device for these diseases should be capable of satisfying an assistive torque about 5-10 Nm with a high velocity value about 360 °/s. The main contribution of the study is to design a mobile, a light weight and an ergonomic wrist orthosis design in which the designed device should have a capability of giving a high value torque support to the wrist with a high velocity value, also. Another contribution of the study is to carry out an electromyography (EMG) based control system in order to keep the user intention at the first place always.

This study introduces the design and the control of an AWO which will interact with the forearm and the hand of the user. The human-machine interaction is mainly satisfied over the EMG signals measured from the forearm muscles which are responsible for the extension and the flexion wrist movements. Contractions of the muscles are detected by using surface EMG sensors and the quantity of the velocity value of the wrist is extracted from a fuzzy logic controller, and then, the actuator system of the AWO comes into play by conveying the necessary torque support to the wrist. Details of the designed AWO and the building of the

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MATLAB/Simmechanics® model are given in Section II. Section III presents the design of the fuzzy logic controller and the signal processing of the EMG signals are explained in Section IV. Section V presents a simulation study for a random wrist motion scenario. Finally, the conclusion and the future works are discussed in Section VI.

II. Design and Dynamic Modeling of the AWO

A. Mechanical Design

AWO should assist the wrist movements in direction of flexion/extension wrist motions and the device user could be able to perform wrist movements in other directions freely. Fig. 1 depicts the solid model of the designed AWO with including actuator system, sensors and all the mechanical parts created by the help of SOLIDWORKS®. As could be seen, a motor system, settled under the forearm, drives the wrist in the F/E directions via timing-belt drive system. Maxon®-EC-4 pole brushless motor, which is having a nominal torque value about *53.5 mNm* and having a nominal speed about *14700 rpm*, and a gearhead, which is having a reduction ratio *104:1*, are chosen as the motor system of the device. Furthermore, there is an optic encoder at the rear end of the motor for controlling the whole actuator system and for measuring the wrist position, also. The total weight of the motor, the gearbox, and the optic encoder is about *238 grams*. A subminiature tension/compression force sensor (Burster® model no: 8417), which weighs only *8 grams*, is located above the device user hand. Therefore, the interacting forces between the device and the user could be directly measured. Hence, the assistive torque to the wrist could be calculated by multiplying the measured force values by the length of the link called *Moment Arm*. Furthermore, the *Moment Arm* link could rotate freely by the help of a revolute joint in order to make the R/U wrists movements. The mechanical parts of the device are to be produced from aluminum to give the structure a relatively light weight, which is only *180 grams*. The two drums are exactly *66 grams* so that the total weight of the device will be about *500 grams* including all the screws, bearings and the timing belt. Thus, the most important design criterions, having a high power and a light weight mechanical structure, will be satisfied. Assuming the drum diameters are the same, the assistive torque will be about (*104×53.5mNm* =) *5 Nm* and the assistive wrist velocity will be about (*14700 rpm/104*=) *848 °/s*. Various drum diameters could be used to increase and/or decrease the assistive torque and the velocity values depending on the device user's occupational application.

B. Simmechanics Model of the AWO

SOLIDWORKS® has a MATLAB/Simmehanics® link which is used to create the dynamic model of the assembled solid parts. Using this link, Simmechanics model of the wrist orthosis was generated as shown in Fig. 2. It is important to note that the actuator system is excluded from the dynamic model for not to overload the solver of the Simmechanics program. But, all the inertia and mass properties of the excluded parts are included into the *Drum 2* properties.

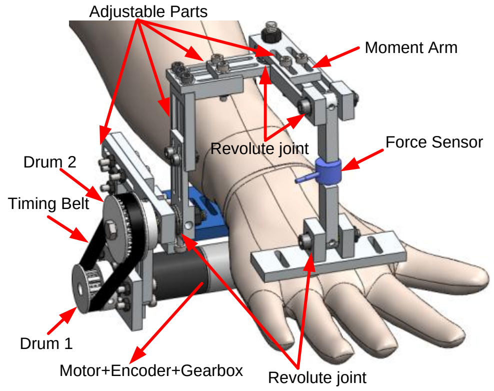

Figure 1.View of the designed AWO

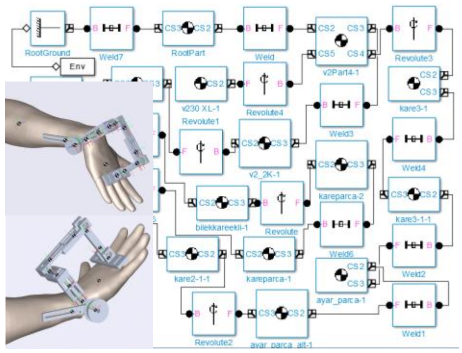

Figure 2. Simmechanics model of the AWO

III. Development of Fuzzy Logic Controller

Fuzzy Logic Controller (FLC) is chosen as the controller of the device since it has a great advantage of allowing multiple inputs and giving out an interpreted output based on the knowledge of the human operator. The first two inputs to the FLC are the EMG signals measured from the forearm muscles which are responsible for the F/E wrist movements. The activation level of the extensor and the flexor muscles will be computed by using a feature extraction method which will be given in Section IV. For safety, the FLC should take into consideration the biomechanical limits of the human wrist joint while driving the actuating system of the device. Therefore, the wrist position will be another input signal to the controller so that there will be totally 3 input signals to the FLC.

As the EMG signals are directly related with the activation level of the muscles, meaning that the higher activation level corresponds to the higher force generated by the muscle, the FLC output could be the wrist torque that should be generated by the motor system or the velocity of the wrist which should be driven by the motor system, also. In that study, the FLC output was chosen as the wrist velocity since the Admittance controller theory, which is one of the most used control theory for rehabilitation robotics systems, is also receives the force as an input and renders the velocity as an output. The schematic of the FLC system is given in Fig. 3. As the output of the FLC will be the reference velocity of the wrist, it is important to note that the motor driver should be in speed control mode.

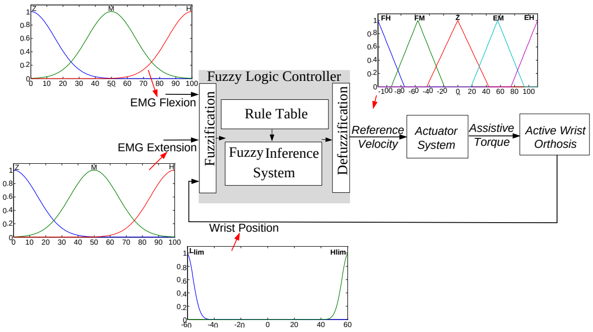

Figure 3.FLC structure and control system of the AWO

MATLAB/Fuzzy Logic Toolbox® is used to create the control system of the device. It is well known that a generic FLC is structured from four main processes which are fuzzification, rule table, fuzzy inference system, and defuzzification. Fuzzification of the input variables using the membership functions, which can have different shapes, is the first step of the fuzzy logic proceeding. For that purpose, EMG signals are fuzzified with the use of 3 Gaussian–shaped membership functions and the wrist position is fuzzified with the use of a Z-shaped and an S-shaped membership functions as shown in Fig. 3. The EMG signals were classified as named with ***Z*** (Zero: 0%), ***M*** (Medium: 50%), and, ***H*** (High, 100%). The wrist position was classified as ***Llim*** (Low limit: -60°) and ***Hlim*** (High limit: 60°). The controller output, which will be the reference velocity value of the wrist in F/E directions, was classified with using 5 Triangular-shaped membership functions and they are named as ***FH*** (Flexion High: -100°/s), ***FM*** (Flexion Medium: -50°/s), ***Z*** (Zero: 0°/s), ***EM*** (Extension Medium: 50°/s), and, ***EH*** (Extension High: 100°/s). The Rule Table constitutes fifteen IF-THEN rule statements which are given in Table I. The first three rules hold the wrist at a fixed position when the extensor and the flexor muscles are activated with a same level. The next six rules determine the direction and the value of the device velocity based on the difference between the activation levels of the flexor and the extensor muscles. The last six rules are the safety rules which will not let the device go beyond the biomechanics limits of the wrist joint. Mamdani type fuzzy inference system is used for mapping the inputs to the output by synthesizing all the 15 linguistic statements written in the Rule Table. Fig. 4 shows the FLC output based on the various activation levels of the EMG signals measured from the extensor and flexor muscles while the wrist position is far away from the safety limits. It is important to note that when the EMG signals are at the same level, the device velocity will always be zero, and the device velocity will rises to a higher values as the difference between the activation level of the extensor and the flexor muscles increases. Fig. 5 shows the entire mapping between the wrist position and one of the EMG signal value while accepting the other EMG signal value is zero. It is obviously seen that the device will be stopped instantly when the wrist position gets near to the predetermined safety regions in order to avoid harmful situations even if the user wants to drive the device beyond the biomechanical wrist limits.

TABLE I. FUZZY LOGIC RULES

No	IF-THEN Rule Statements
1	**If** EMG-Flex is (Z) **and** EMG-Ext is (Z), **then** Velocity is (Z)
2	**If** EMG-Flex is (M) **and** EMG-Ext is (M), **then** Velocity is (Z)
3	**If** EMG-Flex is (H) **and** EMG-Ext is (H), **then** Velocity is (Z)
4	**If** EMG-Flex is (M) **and** EMG-Ext is (Z) **and** Position is not (Llim), **then** Velocity is (FM)
5	**If** EMG-Flex is (H) **and** EMG-Ext is (M) **and** Position is not (Llim), **then** Velocity is (FM)
6	**If** EMG-Flex is (H) **and** EMG-Ext is (Z) **and** Position is not (Llim), **then** Velocity is (FH)
7	**If** EMG-Flex is (Z) **and** EMG-Ext is (M) **and** Position is not (Hlim), **then** Velocity is (EM)
8	**If** EMG-Flex is (M) **and** EMG-Ext is (H) **and** Position is not (Hlim), **then** Velocity is (EM)
9	**If** EMG-Flex is (Z) **and** EMG-Ext is (H) **and** Position is not (Hlim), **then** Velocity is (EH)
10	**If** EMG-Flex is (M) **and** EMG-Ext is (Z) **and** Position is (Llim), **then** Velocity is (Z)
11	**If** EMG-Flex is (H) **and** EMG-Ext is (M) **and** Position is (Llim), **then** Velocity is (Z)
12	**If** EMG-Flex is (H) **and** EMG-Ext is (Z) **and** Position is (Llim), **then** Velocity is (Z)
13	**If** EMG-Flex is (Z) **and** EMG-Ext is (M) **and** Position is (Hlim), **then** Velocity is (Z)
14	**If** EMG-Flex is (M) **and** EMG-Ext is (H) **and** Position is (Hlim), **then** Velocity is (Z)
15	**If** EMG-Flex is (Z) **and** EMG-Ext is (H) **and** Position is (Hlim), **then** Velocity is (Z)

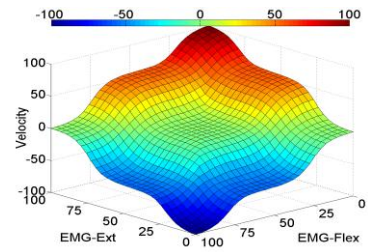

Figure 4. FLC output surface with respect to EMG signals

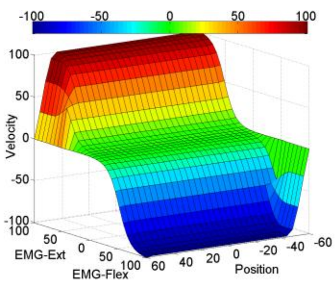

Figure 5. FLC output surface with respect to EMG signals and Position

IV. SIGNAL PROCESSING OF EMG SIGNALS

Raw electromyography (EMG) signals could not be directly used as a control signal for exoskeleton robots due to their complicated pattern. It is well known that EMG signals could be used to generate device control commands after applying some feature extraction methods [10]. Root Mean Square (RMS) is one of the most used feature extraction method, which rectifies the raw EMG signal and converts it to an amplitude envelope. In this study, surface EMG electrodes were placed over the Flexor Carpi Radialis (FCR) and Extensor Carpi Radialis (ECR) muscles, which are responsible for the F/E wrist movements. Raw EMG signals are sampled at *1000 Hz* from the forearm muscles as can be seen from Fig. 6. Then, these raw EMG signals are processed with the RMS feature extraction method with using a data window which consists of the last 256 sampled data. Fig. 7 and Fig. 8 show the sampled raw EMG signals and their RMS values for a random wrist motion scenario measured from the FCR and the ECR muscles, respectively.

Figure 6. Test setup for EMG signal processing.

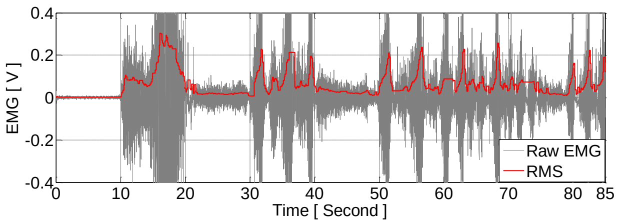

Figure 7. Feature extraction of EMG signal measured from the FCR.

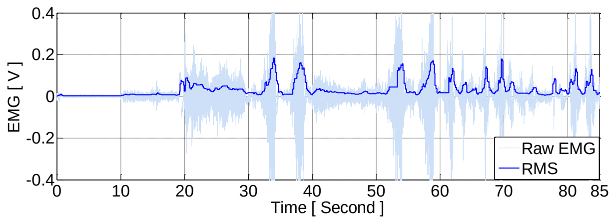

Figure 8. Feature extraction of EMG signal measured from the ECR.

V. Simulation Study of the AWO

Fig. 9 shows the whole simulation model of the AWO comprising from Simmechanics, FLC and EMG signal processing units created before. It is seen that the simulation model accepts the raw EMG signals first, and then, the RMS feature extraction method is used to calculate the mean power of the EMG signals. Since the RMS values of the EMG signals have very small amplitudes, they could not be directly used as an input signals to the FLC. To solve this problem, RMS values are increased to make their nominal values between 0-100 so that the user intention would be identified correctly by the fuzzy inference system. Fig. 10 shows the increased form of the RMS values which would be the first two input signals to the FLC. Wrist position is going to be continuously measured during the simulation, and would be the last input signal to the FLC. Next, the reference velocity calculated by the FLC is used to obtain the reference position and acceleration values, and then, all these 3 reference motion values are used to solve an inverse dynamic problem. Indeed, FLC gives out the reference motion profiles, and then, a joint actuator block, which accepts these reference signals, will drive the revolute joint of the *Drum 2* in the Simmechanics model. Fig. 11 shows the wrist movements for a simulation study based on the raw EMG signals given in Fig. 7 and Fig 8. It is important to remember that positive velocity corresponds to extension wrist movements and negative velocity corresponds to flexion wrist movements. Fig. 12 presents the velocity profile of the wrist, calculated from this simulation study. As could be seen, the wrist velocity and the wrist position are zero for the first 10 seconds of the simulation since the user does not activate any of the ECR or the FCR muscles. For the next 10 seconds, it is seen that the flexor muscle was contracted more than the extensor muscle. Therefore, it is expected that the wrist should make a flexion movement up to hitting the low limit position. Consequently, the wrist started to move in the flexion direction from 10th to 13th second since the RMS FCR was about 30% and the RMS ECR was about 5% and the wrist position was far away from the low limit position. Next, it was obviously seen that the FCL had stopped the actuator system in order to avoid harmful situations for the device user when the wrist position approached to the low limit position at 13th second. Although the device user had been activating his/her FCR muscle with very high levels (80-100%) from 13th to 20th second, fuzzy logic control system did not let the wrist go beyond the low limit position in this time interval due to the 12th rule written in Table I. As the ECR muscle had been being activated more than the FCR muscle from 20th to 30th second, the wrist started to move in the extension direction up to 25th second, but then stopped immediately again when the high limit position (+60°) was reached. From 30th to 40th second of the simulation study; AWO made three times a flexion movement and two times a extension movement as the device user had also contracted his/her FCR and ECR muscles three times and two times, respectively. It is important to note that both the FCR and ECR muscles were being contracted at the same level from 40th to the 50th second so that the wrist velocity was exactly zero during this time period. As could be seen from the rest of the simulation scenario, the device was successfully controlled via EMG signals measured from the forearm. Fig. 13 shows the interaction forces between the device and the user hand. If this force value is multiplied by the length of the *Moment Arm*, which is about *0.08m*, the assistive torque to the wrist could be calculated. Therefore, the maximum assistive torque to the wrist satisfied by the AWO in this simulation study was very small (0.1 *Nm*) since there was not any disturbance or resistive force on the user hand.

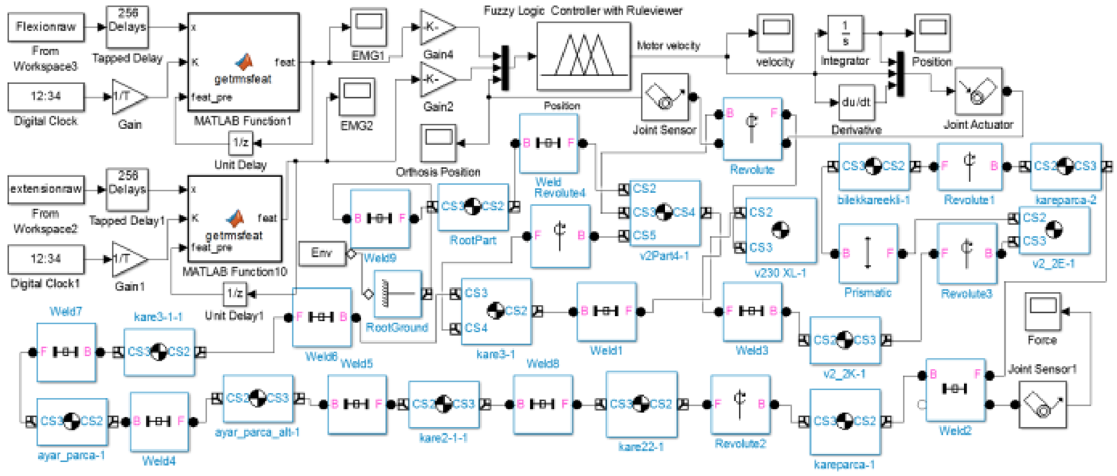

Figure 9. Simulation model of the AWO.

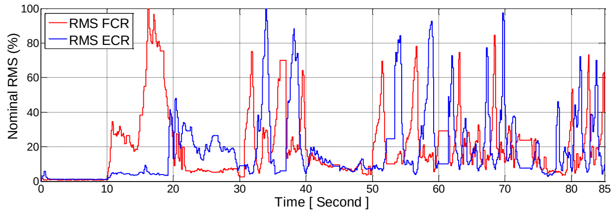

Figure 10. Nominal RMS values of the EMG signals.

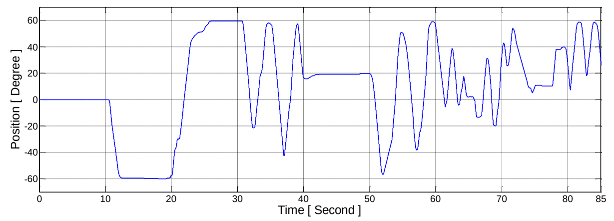

Figure 11.Wrist position.

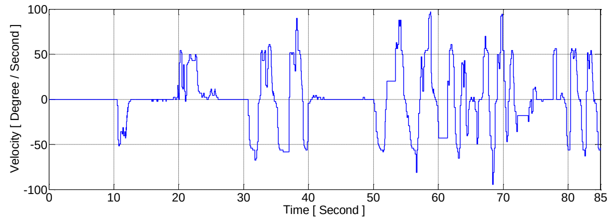

Figure 12 .Wrist velocity.

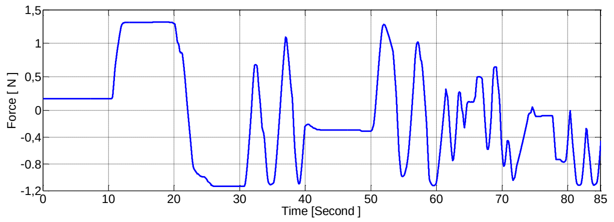

Figure 13. Interaction Force between the device and the user.

VI. Conclusion

In this study, the mechanical design and the fuzzy logic control design of a new active wrist orthosis (AWO) is presented. As the designed device is lightweight, mobile and ergonomic, it could be used for the avoidance or the treatment of tendon torn diseases occurring at the elbow location for the ones who should make repetitive wrists movements due to their profession. A simulation environment is created in order to show the performance of the device. It is shown that the device user could satisfactorily control the AWO based on the real EMG signals measured from the forearm muscles. The future works are to manufacture the AWO and to realize its real-time experiments for those who are suffering from Lateral Epicondylitis and Medial Epicondylitis diseases. Furthermore, the patients with hemiparesis could also use this device for their rehabilitation as the device could be directly controlled via EMG signals. The exact position control of the device and the compensation of the muscle fatigue will be the other future works of the presented study.

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