SEPTEMBER 2019 M.Sc. in Mechanical Engineering EMRE KEKLİKÇİOĞLU

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SIMULATION OF SIGNAL PROCESSING FOR WRIST REHABILITATION

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Prof. Dr. Lale Canan DÜLGER

by

Emre KEKLİKÇİOĞLU

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Emre KEKLİKÇİOĞLU

ABSTRACT

SIMULATION OF SIGNAL PROCESSING FOR WRIST REHABILITATION

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Rehabilitation is defined as an activity enabling a person to perform required mental or physical function. Rehabilitation engineering and use of biomedical signals in rehabilitation are quite promising in recent research studies. Rehabilitation robotics is required to improve quality of elderly people life or easing life of disabled person. Some manipulative operations are necessary especially for daily living activities. Research in this study is directed to get biomedical signals for rehabilitation use. Initially EMG based system is considered with a wrist exerciser. Measurements are taken by volunteer students. Then IMU's (XSens system) are placed, and the experiments with a wrist exerciser are performed. Biomedical signals are intended to understand signals nature with signal processing in wrist rehabilitation use. Finally IMU's are fitted to exoskeleton to improve exoskeleton with robotic rehabilitation.

Key Words: Biomedical Signal, Wrist Rehabilitation, Electromyography (EMG), Motion Tracking, Inertial Measurement Unit (IMU), Exoskeleton with IMU.

ÖZET

BİLEK REHABİLİTASYONU İÇİN SİNYAL İŞLEMENİN BENZETİMİ

KEKLİKÇİOĞLU, Emre
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Danışman: Prof. Dr. Lale Canan DÜLGER
Eylül 2019
50 sayfa

Rehabilitasyon kişinin istenilen zihinsel ve fiziksel işlevi gerçekleştirmesi için gereken aktivite olarak tanımlanmaktadır. Son araştırmalarda rehabilitasyon mühendisliği ve biyosinyal kullanımı oldukça fazla görülmektedir. Bu amaçla rehabilitasyon robotları yaşlı ve/veya engelli insanların yaşam aktivitelerini iyileştirmek için kullanılmaktadır. Sunulan araştırmada biyomedikal sinyallerin bilek rehabilitasyonunda kullanılmak üzere alınması incelenmektedir. EMG tabanlı bir sistem oluşturulup bilek egzersiz aleti kullanılarak laboratuvar ortamında gönüllülerle ölçümler alınıp üzerinde çalışılmıştır. Daha sonra hareket izleme ve rehabilitasyon için kablosuz ölçümde inersiyal ölçüm birimi (İÖB) kullanılmış ve farklı ölçümler alınmıştır. Alınan sinyaller sistem özellikleri göz önüne alınarak değerlendirilmiş ve yorumlar yapılmıştır. Son olarak ise robotik sistemde kullanılmak üzere tasarlanan eksoskeleton ile İÖB ile deneyler yapılmıştır.

Anahtar Kelimeler: Biyomedikal Sinyaller, Bilek Rehabilitasyonu, Elektromiyografi (EMG), Hareket İzleme, İnersiyal Ölçüm Birimi (İÖB), Eksoskeleton ile IMU.

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LIST OF ABBREVIATIONS

ANN	Artifical Neural Network
APL	Adductor Pollicis Longus
ARAMIS	Automatic Recovery Arm Molitityv Integrated System
CCW	Counter - Clockwise
CW	Clockwise
ECR	Extensor Carpi Radialis
ECRB	Extensor Carpi Radialis Brevis
ECRL	Extensor Carpi Radialis Longus
ECU	Extensor Carpi Ulnaris
ED	Extensor Digitorum
EEG	Electroencephalography
EMD	Emprical Mode Decomposition
EMG	Electromyography
EOG	Electrooculography
EXOROB	Exoskeleton Robot
FCU	Flexor Carpi Ulnaris
FCR	Flexor Carpi Radialis
FDS	Flexor Digitorum Superficialis
FEM	Finete Element Method
HOS	Higher Order Statistics
ICA	Independent Component Analysis
IHMT	IMU- Based Human Motion Tracking
IMU	Inertial Measurement Unit
MAP	Muscle Action Potential

MCSs	MyoElectric Control Systems
MMI	Man-Machine Interface
MU	Motor Unit
MUAP	Motor Unit Action Potential
PL	Palmaris Longus
RBSM	The Rigid Body Spring Method
ROM	Range of Motion
RSSI	Received Signal Strength Indicator
SEMG	Surface Electromyography
SVM	Support Vector Machine
WA	Wavelet Analysis
WWBAN	Wearable Wireless Body Area Networks

CHAPTER 1

INTRODUCTION

1.1 Introduction

Rehabilitation exercises are not very complicated, so they can be performed using robots reducing the cost and time during recovery periods. Biosensors can process available data by using biomedical signal processing techniques. This is necessary to be interpreted by human or automated sense for clinic or rehabilitation use. Assisted rehabilitation is necessary for necessary of neuromuscular capabilities. So therapists assist and guide a patient to perform some exercises. Nowadays, this is done by robotic devices offering patients independent rehabilitation; especially human-machine interaction is available.

1.2 Background on EMG Based Systems

EMG signals are used most of the time in Biomedical Engineering. Three main applications are seen as; an indication for activation of muscle, relation for force produced by muscle and fatigue processes for muscle. EMG refers to electromyography which studies muscle electrical signals. Some studies use EMG as myoelectric activity. Muscle tissue definitely conducts electrical potentials under interest. These electrical signals refer mostly as the muscle action potential (MAP). When the EMG signals are recorded, two main issues are concerned for signal. One is taken as the signal-to-noise ratio. The second one is considered as signal distortion. Two types of electrodes have been available to get muscle signal. They are named as *invasive electrode* and *non-invasive electrode (sEMG).* These electrodes can be dry or with gel layer. EMG is acquired from surface electrodes directly on the skin. The signal takes all the muscle fiber action potentials which are active in the muscles. These action potentials are seen during random intervals. EMG signal may give either positive(+) or negative(-) voltage while performing measurements. Individual muscle fiber action potentials are taken by using wire or needle electrodes placed. Needle electrodes are generally preferred neuromuscular actions. MUAP (motor unit action potential) is commonly studied as the combination of the muscle fiber action potentials from all the muscle fibers of a single motor unit. MUAP can be detected by a skin surface electrode (non-invasive case) located near this field, It can be taken separately by a needle electrode (invasive case) which is inserted in the muscle. Surface EMG (SEMG) records the information actually present in these (MAPs) muscle action potentials. Invasive electrodes give clear signal with high-signal to noise ratio. Thus diagnosing muscle illness can be very accurate.

Neurological and neuromuscular problems are diagnosed by EMG signals clinically. EMG signals are also utilized in many laboratories. Biomechanics, motor control, neuromuscular physiology, movement disorders, postural control, and physical therapy can be seen for example. Surface electromyography (SEMG) has been used to control assistive devices like hand prostheses, hand exoskeletons upper and lower exoskeletons. The duration, peak to peak amplitude and the number of phases are 3 parameters to MUAP [1, 2]. There are various methodologies and algorithms to take and utilize SEMG and signal processing particularly in biomedical field. A. N. Morali and M. H. M. Som [3] were reviewed most of studies. A guide for EMG signal acquisition is given as amplitude estimation, frequency analysis to be used for prosthesis as non-invasive approach.

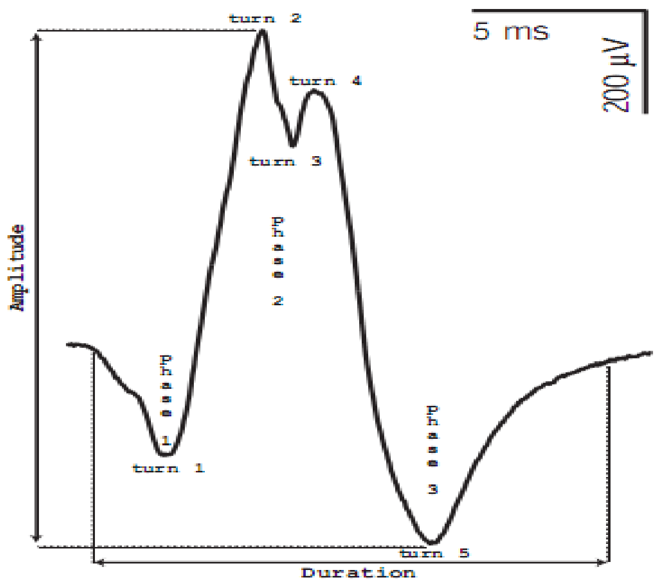


Figure 1.1 MUAP Parameters [2]

U. Mayetin et al [4] presented a study a robot application with the EMG signals. They controlled velocity and direction of a mobile robot with the EMG signals simultaneously obtained from three channels on the forearm. The EMG signals on the forearm and wrist are evaluated in clinical health studies, biomedical case studies for example. Some studies are seen controlling mobile robots using sEMG signals. C. Tepe et al [5] have designed a system for predicting opening and closing of the hand speed. SEMG data is used later for rehabilitation. They utilized from SVM to predict constant speed of hand movements which is acquired from a healthy human achieving % 96 correct classification values. E. Z. Engin et al [6] have investigated multi-functional forearm movements by taking EMG signals from forearm muscles. These signal properties can be utilized for rehabilitation purposes. M. S. Çelik and İ. Eminoğlu [7] have performed a study on EMG classification algorithm for upper limb prostheses. Eigth different upper limb movements (hand open, hand closed, flexion, extension, pronation, supination, abduction and adduction) are recognized with fuzzy logic using surface electrodes. The system is not suitable for real time applications and need to rearrange the algorithm for different individuals. E. J. A. Mireles et al [8] have presented robotics assisted rehabilitation is revealed. The upper limb EMG patterns are analysed for diagnosis. Experimental results are given for healthy volunteers and stroke patients . C. Yang et al [9] have controlled a robot arm by utilizing sEMG signals. A haptic device OMNI is used to control Baxter® robot arm. Potential applications are seen as tele-rehabilitation and tele surgery in many studies. MYO armband is applied for detecting EMG signals. A tele operated robot this used to imitate human writing skills using electromyography (EMG) signals. A MYO sensor is used to measure the surface electromyography (sEMG) signals. These signals are generated by contractions of human muscles needed for writing tasks. A low pass filter is used to process the EMG data. A haptic device is applied to control a robot arm which imitates writing skills. They succeeded writing recognizable words with the designed robot.

M. Sasaki et al [10] have then described a robot control system which uses Electrooculography (EOG) and Electromyogram signals to control the robotic gripper. Mastication is necessary to get EMG signal of interest. The uArm^{TM} robot is successfully controlled for the man-machine interface (MMI) to be feasible especially for elderly person for example. The signal is acquired by EMG electrode and EMG method is used for grasping an object application of robot control. They have classified EMG signals into five patterns for control the degree of gripping input. A. Balbinot et al [11] have classified movements of the arm using 3 pairs of SEMG as shown in Figure 1.2. Signals are then classified using ANN's. The classification of six movements (the hand contraction, the wrist extension, the wrist flexion, the forarm flexion and finally the forearm rotation) are performed 68%-88%. Three muscles; (Flexor Carpi Ulnaris-Channel I), (Extensor Carpi Radialis-Channel II) and (Biceps-Channel III) are used. The study is investigated movements of the forearm buy using only three surfaces electrode pairs located in places of concern. They detected forearm surface electromyography signals and they utilized artificial neural Networks for classification of several arm movements. They achieved good accuracy rates although the EMG signals acquired from only three places.

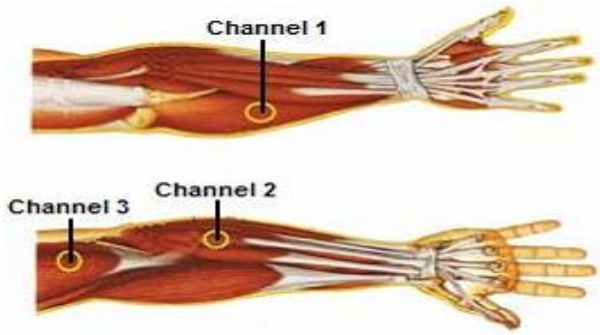


Figure 1.2 SEMG Placed [11]

R. H. Chowdhury et al [12] have suggested processing of EMG signals. These systems are called as MyoElectric Control Systems (MCSs). EMG signal processing can be performed using Wavelet Analysis (WA), Higher Order Statistics (HOS), Emprical Mode Decomposition (EMD), Artificial Neural Network (ANN), and Independent Component Analysis (ICA) for example. These signals are analysed in medical and physiological applications for diagnosing purposes.

I. Saad et al [13] presented a work to classify human muscle strength for clinical rehabilitation application. They obtained EMG signal from human muscle using non-invasive electrodes in a single channel. Later process is completed by signal acquisition circuit to get signal to be used. They classified EMG signals into six different levels to determine the muscle strength level of individuals. They achieved similar patterns for ten experiments.

M. Novak designed [14] an arm exoskeleton controlled by the EMG signal. It is taken by using the biceps muscle and used to amplify the force delivered by the biceps brachi with an exterior support structure. The force to be applied is determined from the amplitude of EMG signal. They controlled successfully left arm exoskeleton to amplify the power exerted by the bicep.

A.V.S. Rana and R. Aggarwal [15] controlled a 2-d robotic arm by using EMG signals. The EMG signals are acquired using three muscle groups on the upper forearm. They have concluded a work to get clear EMG data from noisy signals. The data is then used as a control signal for robotic arm.

1.3 Background on Inertial Measurement Unit (IMUs) for Rehabilitation

Motion tracking has got the attention especially non-invasive sensors in the recent years Inertial measurement units (IMUs) for rehabilitation purposes. IMUs include accelerometers and gyroscopes. Motion capture issues and their exoskeleton use for rehabilitation are taken into consideration in background study.

H. Zhou et al [16] have provided a survey of technologies for human movement tracking systems. Human motion tracking has been performed non visual tracking (inertial based, magnetic based, other sensors, glove based), visual tracking (based on visual marker, marker-free and visual, combinatorial tracking) and robot-aided tracking. All of them are summarized with their limitations and merits during rehabilitation. A. Filippeschi et al [17] have presented a review on IMU-based human motion tracking (IHMT) and used methods in various applications. Medical ones are interested in this study. Generic limp orientation, lower limbs tracking, upper limps tracking, full body motion tracking were performed. Y. Jung et al [18] have introduced motion tracking method by using wearable inertial sensors. Upper body movement in real time was tracked. The 3D human upper body model is built using the estimated joint variables. Flexion/Extension (F/E) angles are found on hinge, saddle. T. Seel et al [19] have measured joint angles for gait analysis. Inertial measurement unit used to calculate hinge joint angles on the human body. Flexion/extension angles are calculated for hinge, saddle and spheroidal angles. R.

Peres et al [20] have presented an inertial sensor based monitoring system. Upper limb movements are measured and analysed. Four inertial sensors are mounted on thhe human upper limp kinematic model is built. A portable motion capture system is proposed using MTi XSens units. S. Andrews et al [21] have presented real-time tracking of human using IMUs and optical markers. A person with 6 IMUs and 5 optical markers are placed for tracking. Thus markers and IMUs are located at the head, hands, and feet.

1.4 Background on Wrist Rehabilitation

P. Maciejasz et al [22] have presented a detailed study on robotic devices to provide a survey for upper limb rehabilitation, Two hundred five research studies were searched and given in a table as DOF, supported movements, actuators, main control inputs and field of application. E. Akdoğan presented [23] robotic systems are used passive, active, and active-assistive purposes. Many robotic systems were applied for lower and higher extremity rehabilitation. Some of the systems have utilized virtual reality techniques for rehabilitation. Trainings for upper limp rehabilitation were also taken as passive, active-assistive and resistive exercises. Many recordings and measurements were taken to see muscle activation. Later haptic interfaces are used to perform virtual and remote environment to the user by considering biomechanics issues. Some studies were chosen from all to explore wrist rehabilitation.

M. H. Rahman et al [24] have designed 2 DOF exoskeleton robot (Exorob) developed to rehabilitate the elbow and wrist movements in Figure 1.3. A kinematic model of the robot is developed and modeling and control performed. D. D. Auria et al [25] have performed a haptic system for wrist rehabilitation; IMT3, MIME, Rice Wrist, HWARD, the Okayama University Pneumatic manipulator were used for rehabilitation in health centers. These are all considered on robot assisted therapy.

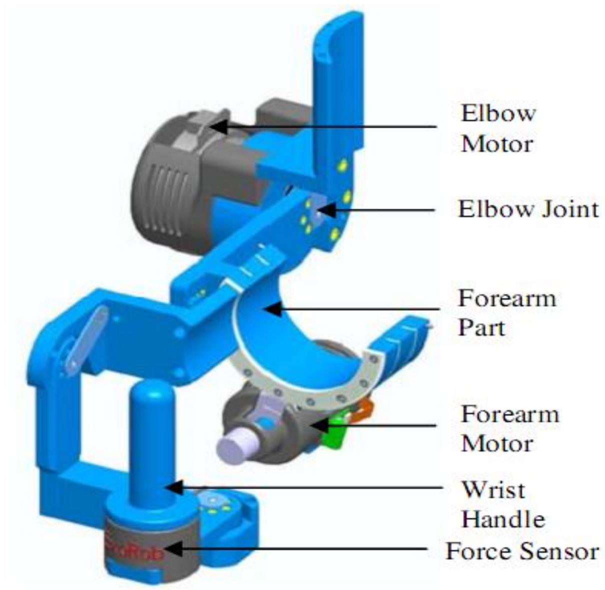


Figure 1.3 Elbow and forearm motion exoskeleton [24]

N. Omerkulov et al [26] have presented so called exoskeleton robot. NU-Wrist for therapy exercising. A prototype has been designed and produced by using 3D printers as shown in Figure 1.4. The workspace is tested wrist movements for FE, AA and PS motions in healthy subjects for example.

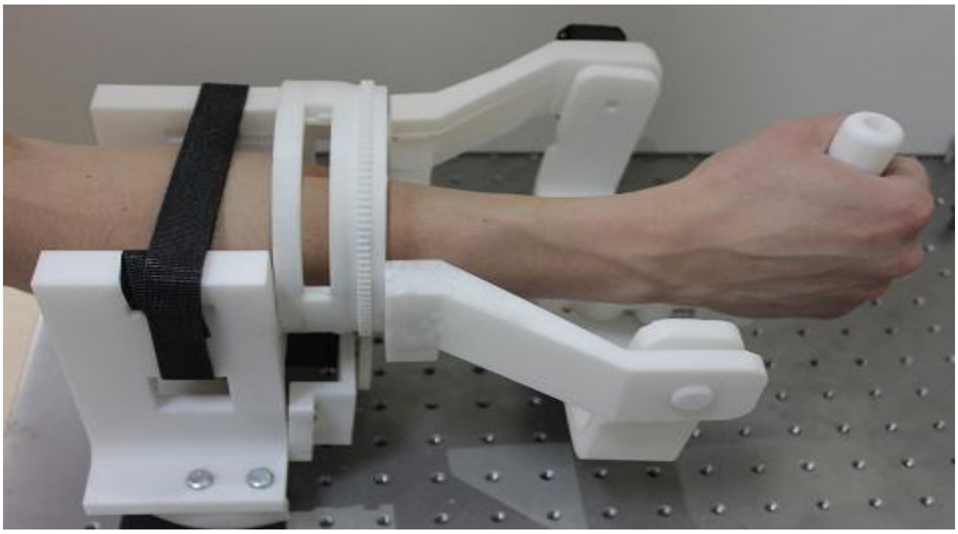


Figure 1.4 NU-Wrist Rehabilitation [26]

S. Guo et al [27] have proposed a VR based self-rehabilitation system utilizing the virtual training model. EMG signals were taken from the subject for motion recognition in Figure 1.5. Five healthy volunteers were used by taking sEMG signals.

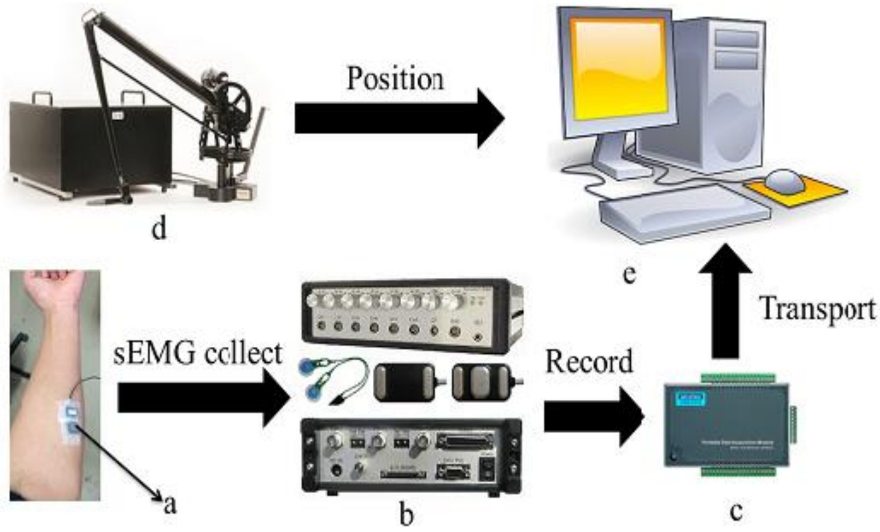


Figure 1.5 Rehabilitation systems [27]

L. Colizzi et al [28] have designed a system so called ARAMIS (Automatic recovery arm motility integrated system) for rehabilitation of upper limb. This is explained as a master-slave exoskeleton robot.

Guraliuc et al [29] suggested Wearable Wireless Body Area Networks (WBAN) based approach. The principal activities of human arm are evaluated. The data collected by wearable sensors. They have presented an algorithm based on the Received Signal Strength Indicator (RSSI). This is applied in order to identify and classify the rehabilitation algorithms. The arm movements are classified. They then used an SVM learning technique by achieving good detection performances for preliminary tests.

1.5 Motivation of the Work

Relationship between EMG signal and human wrist is studied for rehabilitation purposes. The training for rehabilitation can be achieved using exoskeleton system guiding patients. So the trajectories for daily activities are to be studied with wrist kinematics. Alternatives using EMG and IMU are revealed with suggestions. This study is performed to explore use of EMG systems and IMU's while making an alternative between their applications. Their use and problems encountered are given at the end for rehabilitation.

1.6 About Thesis

This thesis is devoted to give a background on EMG signals and IMU's for rehabilitation. Electromyography (EMG) is used to record the muscle activity electrically. Muscle contraction and relaxation causes EMG signal which are taken, evaluated and then utilized in biomedical use. Chapter 1 gives an overview of EMG based systems and wrist rehabilitation using bio signals. Chapter 2 is about wrist anatomy and kinematics. Use of EMG system is searched in Chapter 3 with wrist exerciser. IMU characteristics were included with measurements in Chapter 4. Their use in wrist rehabilitation is also included. Chapter 5 gives discussions and recommendations for future.

CHAPTER 2

WRIST ANATOMY

2.1 Introduction

To perform rehabilitation initially wrist anatomy and motion analysis are studied by considering anatomical structure of a human wrist. Daily activities of wrist during living are taken into consideration. Kinematics of wrist is revealed with previously studied models.

2.2 Wrist Anatomy

The human wrist with the forearm has got 3 DOF's. The forearm performs pronation and supination (PS motion). Actually PS is not a movement, but it has great effect on hand and wrist functions in daily life. The wrist performs flexion and extension as FE motion, abduction (radial deviation) and adduction (ulnar deviation). Thus the wrist is a universal joint with 2 DOF using two orthogonal axes. So the wrist allows movement along two axes performing flexion (F), extension (E), adduction-ulnar deviation (A) and abduction-radial deviation (A) at the wrist joint as shown in Figure 2.1. A correspondence can be given by using a clock model from the neutral axis in Figure 2.2.

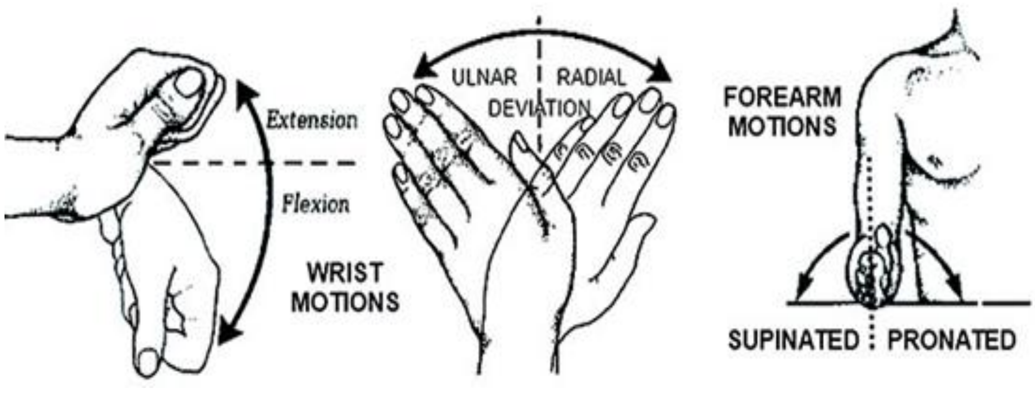


Figure 2.1 Movements of the wrist and forearm [30]

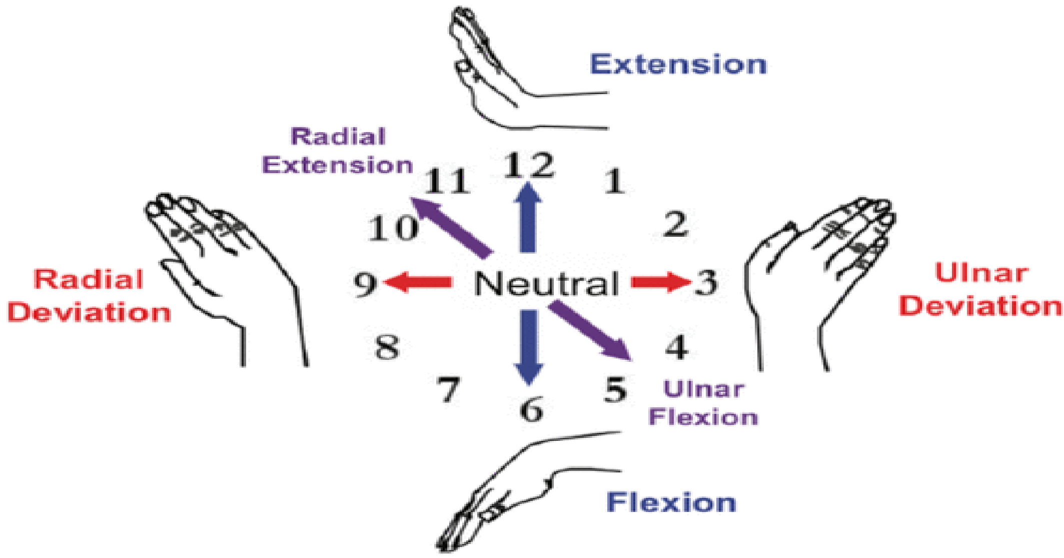


Figure 2.2 Movements of the wrist only [31]

The first one is antero-posterior axis for AA and the second one is transverse axis for FE. The ranges of motion for PS vary from 85º to 90º. The radial deviation (abduction-A) is 15º, ulnar deviation (adduction-A) is up to 45º as the wrist is kept in neutral position [26]. In reference studies; arc of 45º (10º flexion, 35º extension) is sufficient for performing daily activities. For example; 5º flexion to, 35º extension is necessary for eating, drinking and reading simply for daily activities. Two motion axes are given in Figure 2.3 for human wrist joint. The wrist joint muscles with primary function are called as the anterior muscles (Flexor Carpi Ulnaris-FCU, Flexor Carpi Radialis-FCR and Palmaris Longus) and the posterior muscles (Extensor Carpi Radialis Brevis-ECRB, Extensor Carpi Ulnaris-ECU.

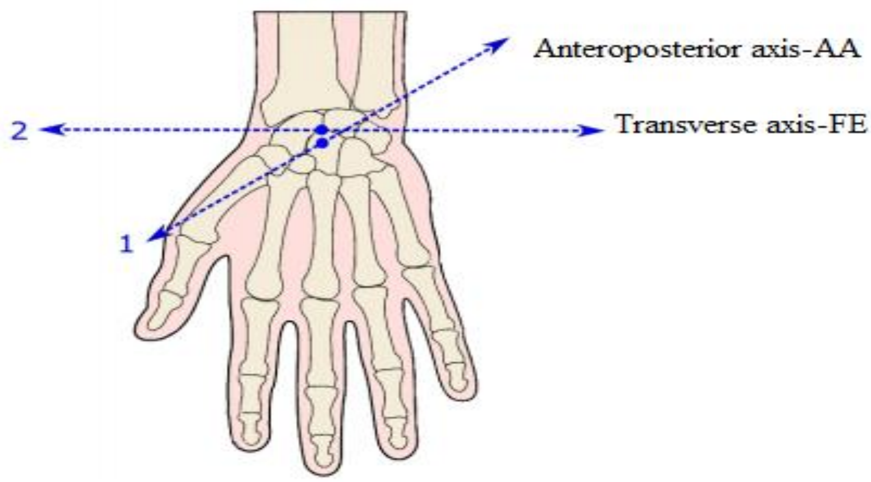


Figure 2.3 Axes for human wrist joint [26]

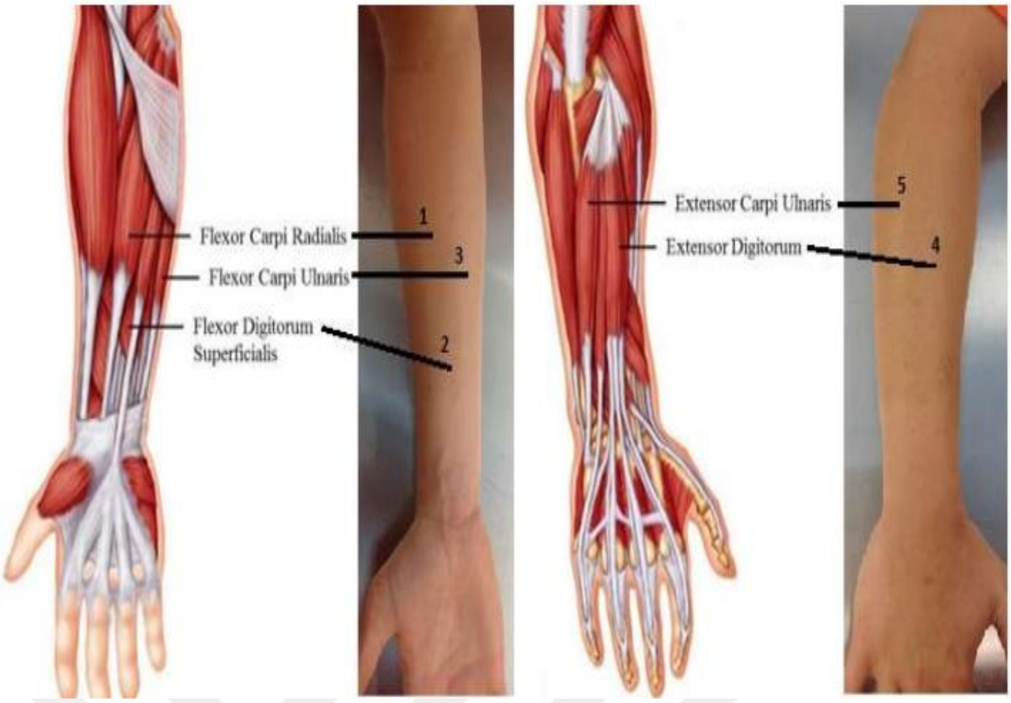


Figure 2.4 Muscles used in sEMG acquisition (1) FCR, (2) FDS, (3) FCU, (4) ED and (5) ECU. [32]

The muscles of the forearm perform all the movements needed for the joint given in Table 2.1.

Table 2.1 Muscles for wrist motion [33]

Wrist Motion	**Muscles**
Extension-bending the wrist backwards	Extensor Carpi Radialis Longus (ECRL-prime mover), Extensor Carpi Radialis Brevis (ECRB-prime mover), Extensor Carpi Ulnaris, Extensor Digitorum (assists only)
Flexion-bending the wrist towards the palm.	Flexor Carpi Radialis (FCR-prime mover), Flexor Carpi Ulnaris (FCU-prime mover), Palmaris Longus, Flexor Digitorum Superficialis (finger flexor-assists only)
Abduction	Adductor Pollicis Longus (APL), Flexor Carpi Radialis (FCR), Extensor Carpi Radialis Longus (ECRL) and Brevis
Adduction	Extensor Carpi Ulnaris (ECU), Flexor Carpi Ulnaris (FCU)

Here flexor Carpi Ulnaris (FCU) is achieves the wrist flexion with ulnar deviation. Palmaris Longus (PL) helps the wrist flexion. Extensor Carpi Radialis (ECR) assists in extension and radial abduction of wrist. Extensor Digitom is responsible from four fingers extension and also the wrist extension (forward/backward)

2.3 Kinematics and Dynamics of Wrist

There are biomedical studies in literature, which are about the kinematics of the wrist. S. Fischle [34] has developed a computational model for the wrist by using rigid body spring method. He has then compared the computed results with kinematic measurements using both cadaver specimens and living subjects. Range of motion (ROM) is used for the extreme joint motions. The rigid body spring method (RBSM) is applied. The finite element method (FEM) was applied to get patterns of stress and strain. The software RecurDyn^{TM}-V6.1 was used for rigid body dynamic analysis. The bone geometries were taken as rigid body volumes. Figure 2.5 shows RBSM model in RecurDyn representing a right human wrist where the ligaments are given in red and tendons are black dashed lines. The contact surfaces are dark blue.

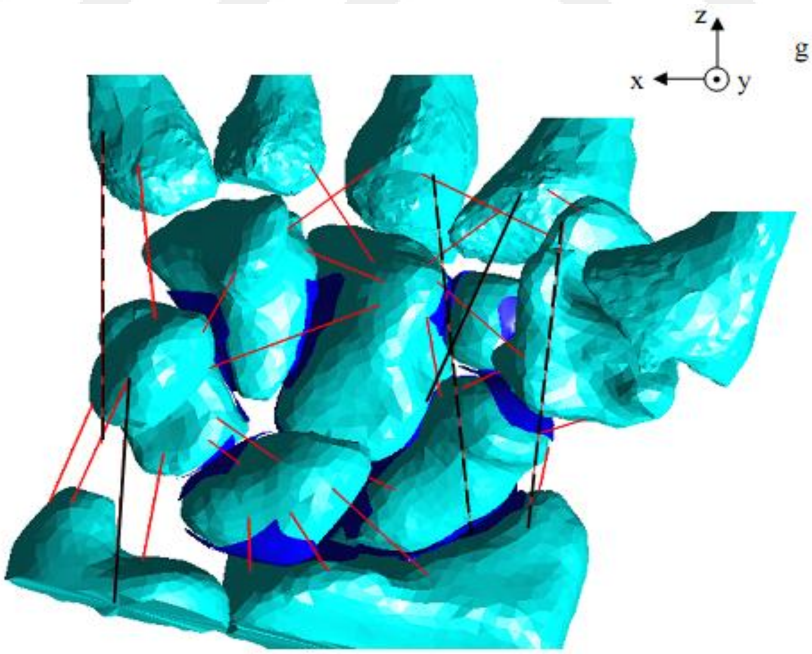


Figure 2.5 RBSM Model in RecurDyn-A right human wrist [34]

M.A. Murphy et al [35] have performed a study on the wrist movements by placing markers during daily activities. Activity of daily cyclical task; drinking is chosen for example. Nine markers were used and data for the whole activity were taken. Movement times, peak velocities were determined, and the joint angles were computed. They can be later used with statistics for rehabilitation purposes.

S.K. Charles [36] has presented a Ph. D study including kinematics and dynamics of the wrist including mathematical model of the wrist. Generalized coordinates were defined with dynamics of wrist rotations and calculated wrist stiffnesses (10 subjects were used.). A 2 DOF wrist model equations were derived via Lagrange's equations. Thus it is being represented as a universal joint with 2 DOF, where β is the angle in flexion-extension, and γ is the angle in radial-ulnar deviation as shown in Figure 2.6. A universal joint with non-intersecting axes inclusion of stiffness and gravity was considered. Since this thesis only considers biosignal base, these details are excluded in the study.

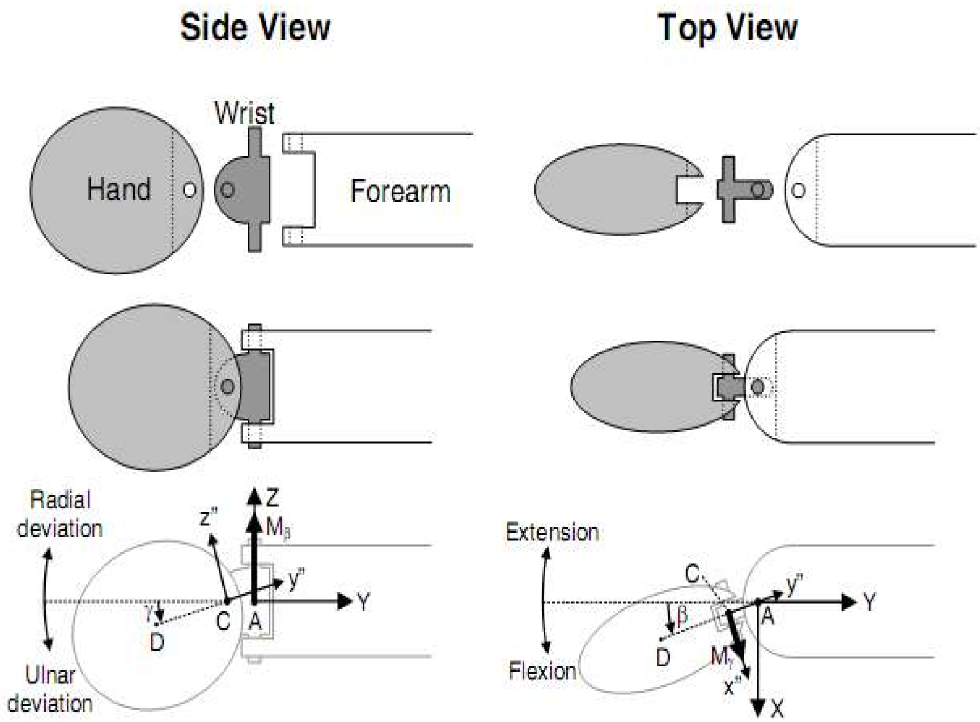


Figure 2.6 Model wrist rotations [36]

CHAPTER 3

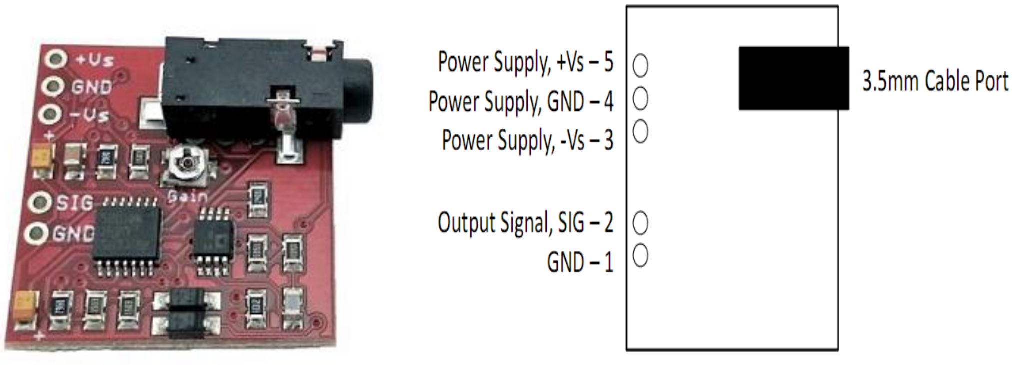
EMG MEASUREMENT-EXPERIMENTAL SYSTEM SET UP

3.1 Introduction

Bio signal based control systems are utilized as stationary systems; signal based robotic systems or exoskeletons by monitoring for purpose of rehabilitation. EMG measurement system and the measurements taken for rehabilitation are described, and presented in this chapter. A wrist exerciser and a passive exoskeleton are used during all measurements. Initially the system is described, and then the circuit characteristics are given. Next three volunteers (healthy subjects) are helped during measurements for the wrist.

3.2 Description of EMG System

EMG signals were obtained based on a system, which has Muscle sensor V3, by Advancer Technologies®. Three-lead differential Muscle/Electromyography sensor is attached to arm. It can be used for robots, medical devices and exoskeleton units that has been used for pre medical research in this thesis. The sensor board is given in Figure 3.1(a) and (b). Board specifications are included in Table 3.1. The muscle sensor has got a sensor board, a cable for connecting electrodes to the sensor board, and 6x24 mm sample electrodes. The sensor amplifies and processes the electrical activity of the muscle. It can be used with ADC.



(a) (b)

Figure 3.1 Three-lead differential muscle/electromyography sensor board [37]

Table 3.1 Electrical specifications of board [37]

Parameter	Min.	Type	Max.
Power Supply Voltage (V_s)	±3 V	±5 V	±18 V
Gain Setting, Gain=207*(X/1kΩ)	0.01Ω (0,002x)	50kΩ (10,350x)	100kΩ (20,700x)
Signal Voltage (Output)	0 V	---	$+V_s$
Differential Voltage (Input)	0 mV	2-5 mV	$+V_s$/Gain

The EMG sensors works with the Arduino microcontroller. The Arduino only reads input values changing 0-5V. The sensors produce the output values in range of ±5V. Thus signal level is to be adjusted for amplification. The resistor was replaced with a potentiometer 0-5kΩ. The potentiometer resistance is changed to change the signal amplitude (set to 2.5V). The signal range is then changed from [−2.5V, 2.5V] to [0V, 5V]. An offset voltage (2.5V) is added to each signal. The Op-Amps (A–B) are used for stabilizing 2.5V (the reference signal and the input signal). Op-Amps (C-D) are used for adding them together, but later for inverting the sign; negative (-) to positive (+). This sensor produces analog output voltage A. Next the battery is connected to get power supply to the sensor. There is also isolation amplifier (ISO124) with Arduino boards. The isolation amplifier and battery are used to isolate the user and the electrical grid. Schematic representation of the circuit is given in Figure 3.2.

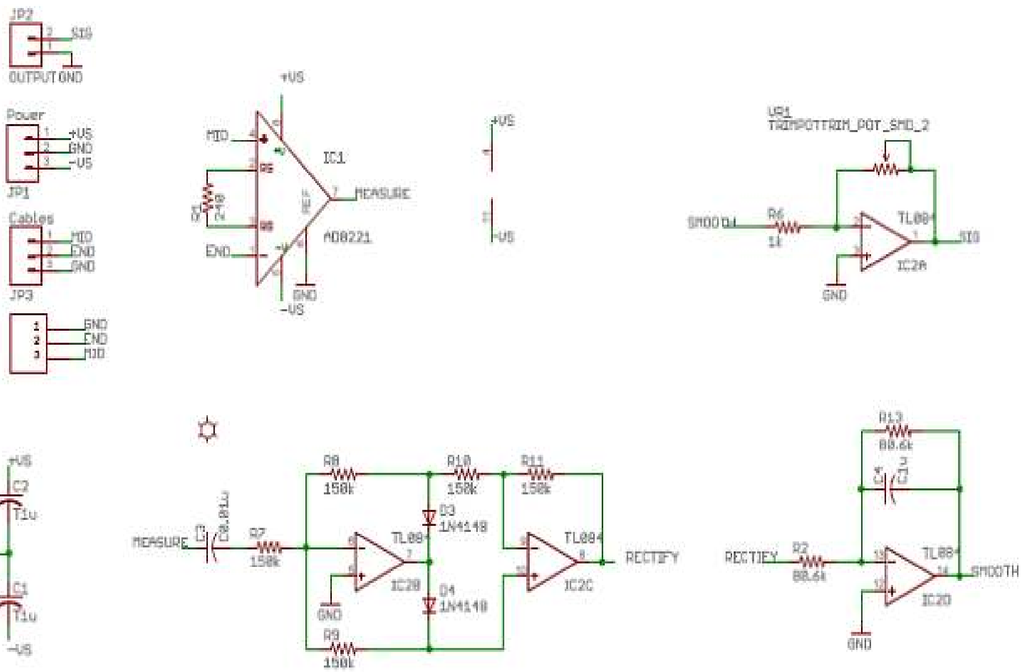


Figure 3.2 Schematic Representation of Circuit [37]

The battery is connected to provide separate power supply to the sensor and the isolation amplifier (ISO124) between Arduino board. Here isolation amplifier and battery provide isolation between user and electrical grid. Arduino/Genuino Uno is installed on PC. The Uno is then programmed by using the Arduino Software, Integrated Development Environment (IDE) common to all boards. Uno board is connected with an USB printer cable. The SD library allows for reading from and writing to SD cards. The library supports FAT16 and FAT32 file systems on standard SD cards. The file names passed to the SD library functions have the paths given by forward-slashes, /e.g. "directory/filename.txt". Here SD card was used for EMG data storage measurements during Mechatronics Laboratory. Exported file extension is saved as '.csv'. So the data analysis is performed by Excel®. Schematic representation of sensor connections is given in Figure 3.3.

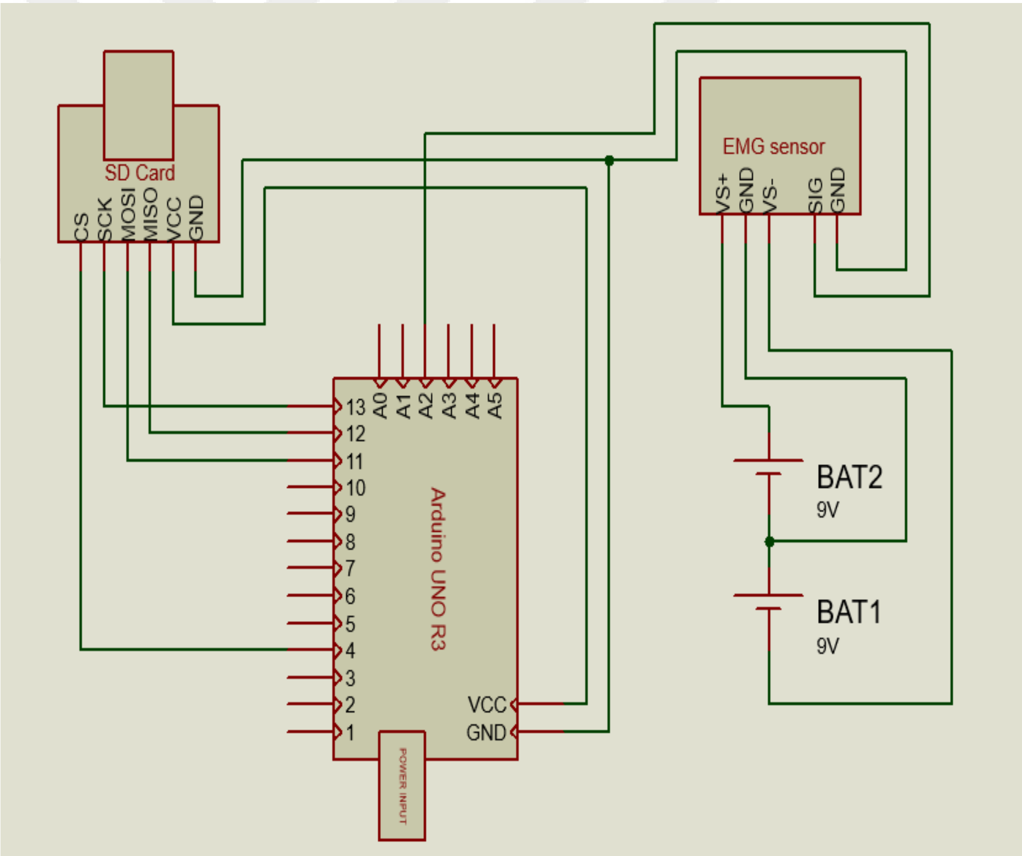
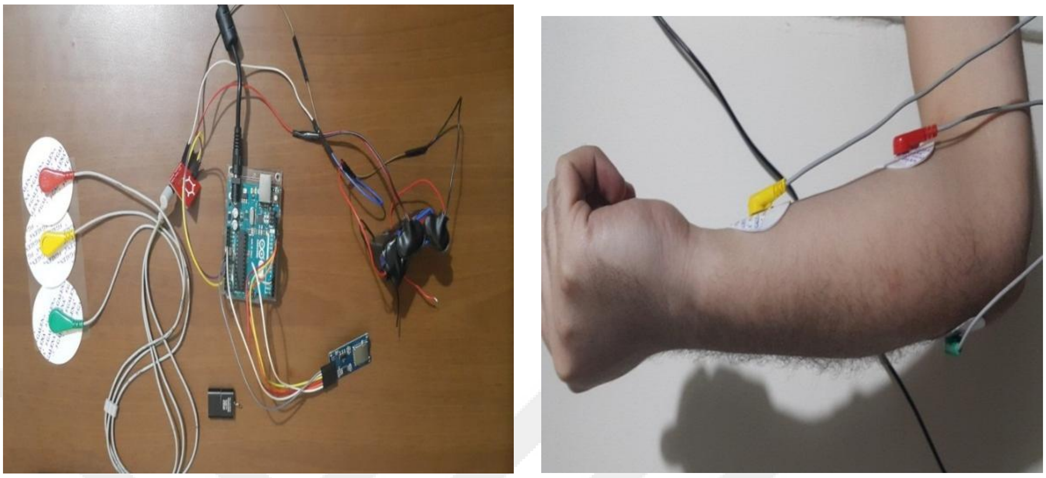


Figure 3.3 Schematic representation of sensor

Three electrodes are used for measurements; two represent positive (+) electrodes which are one for negative (-) as a reference connected to the subject's body. They are disposable electrodes adhering well to the skin. They are used for short-term monitoring as shown in Figure 3.4(a) and (b).



(a) (b)

Figure 3.4 Disposable electrodes and the experimental system (Subject I)

3.3 Wrist Exerciser

Wrist Exerciser has been preset at the minimum resistance level (1=minimum, 5=maximum). The tension adjuster is turned to clockwise (CW) to increase the resistance. Similarly, the resistance is decreased by turning it to counter-clockwise (CCW). A metal clip is provided together with the Wrist Exerciser. This small object will protect you from over expanding your wrist, when placed over the extension wire. Wrist Exerciser may be used while standing or in a seated position. The following exercises have been designed to provide maximum benefit to the wrist and forearm muscles. Wrist exerciser is shown in Figure 3.5 which is then tested for the spring stiffness. Different weights are used for testing purposes to see deformation of the wire properly; 2 kg, 3 kg and finally 5 kg for example [38]. Wrist exerciser detailed drawings are included in Appendix.

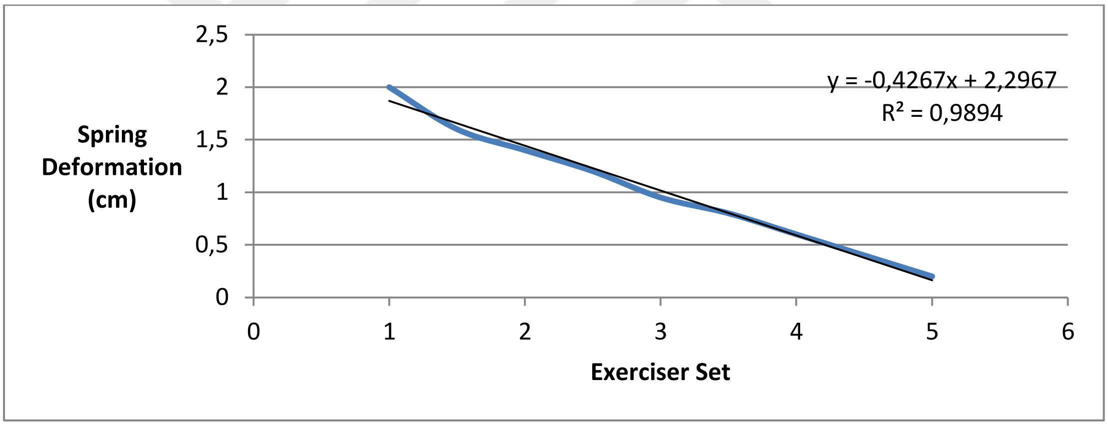
Figure 3.5 Wrist exerciser

Wrist exercises are shown in Figure 3.6 as Exercise I-II. A steel wire is being used in the exerciser. Spring deformations are measured and they are given in Table 3.2 as showing linear behavior. To see what happens M=2 kg deformations are given in Figure 3.7 (a) and (b) for M=3 kg. respectively.

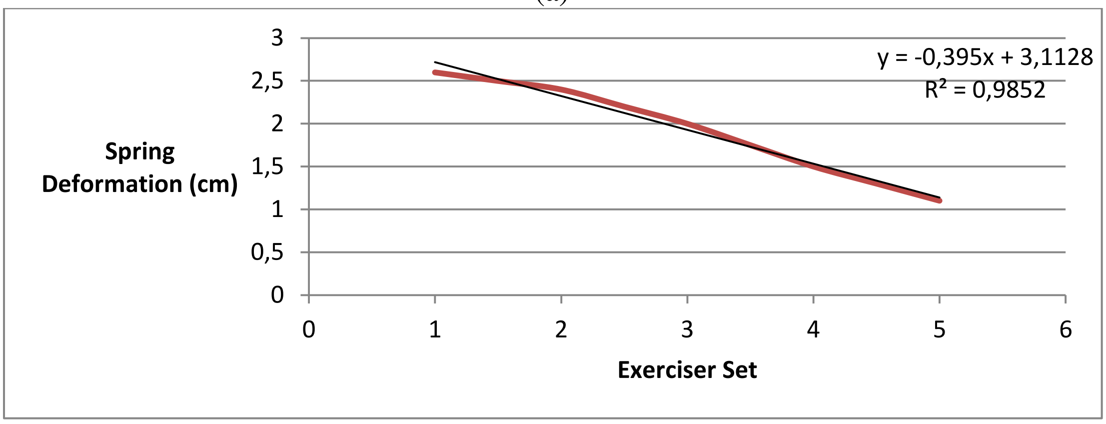
Figure 3.6 Exercise I-II

Table 3.2 Deformations for wire spring

Exerciser Set (Min-Max)	Elongation (cm) M=2 kg Y=-0,4267x+2,2967	Elongation (cm) M=3 kg Y=-0,395x+3,1128
1	2,0	2,6
1,5	1,6	2,5
2	1,4	2,4
2,5	1,2	2,2
3	0,95	2
3,5	0,8	1,75
4	0,6	1,5
4,5	0,4	1,3
5	0,2	1,1



(a)



(b)

Figure 3.7 Different settings for spring; M=2 kg and M=3 kg.

3.3.1 EMG Data -Subjects Using Wrist Exerciser

Two subjects are chosen for the tests using wrist exerciser. (Subject I- Male: Age=23, Weight=83 kg, Height=1.83 m; Subject II-Male: Age 24, Weight=76 kg, Height=1.79 m) Experiments with EMG using two subjects are performed using Extension/Flexion movements, pronation/supination and finally radial and ulnar deviation of the wrist. Figure 3.8 shows range of motion for ulnar/radial deviation [39]. Tests were performed at Gaziantep University, Mechanical Engineering Dept., Mechatronics Laboratory as a part of student graduation projects. Three different settings (1-3-5) were used with wrist exerciser for flexion/extension movements shown in Figures 3.9 and 3.10.

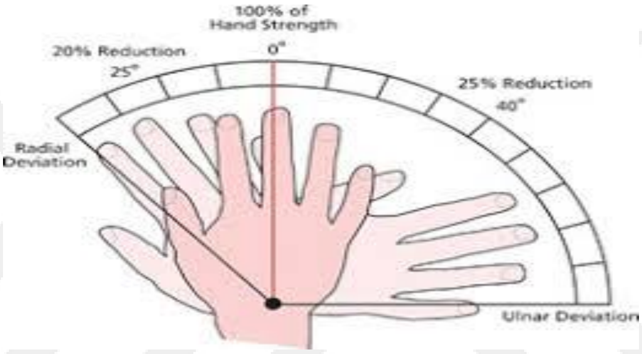


Figure 3.8 Range of motion for radial/ulnar deviation [39]

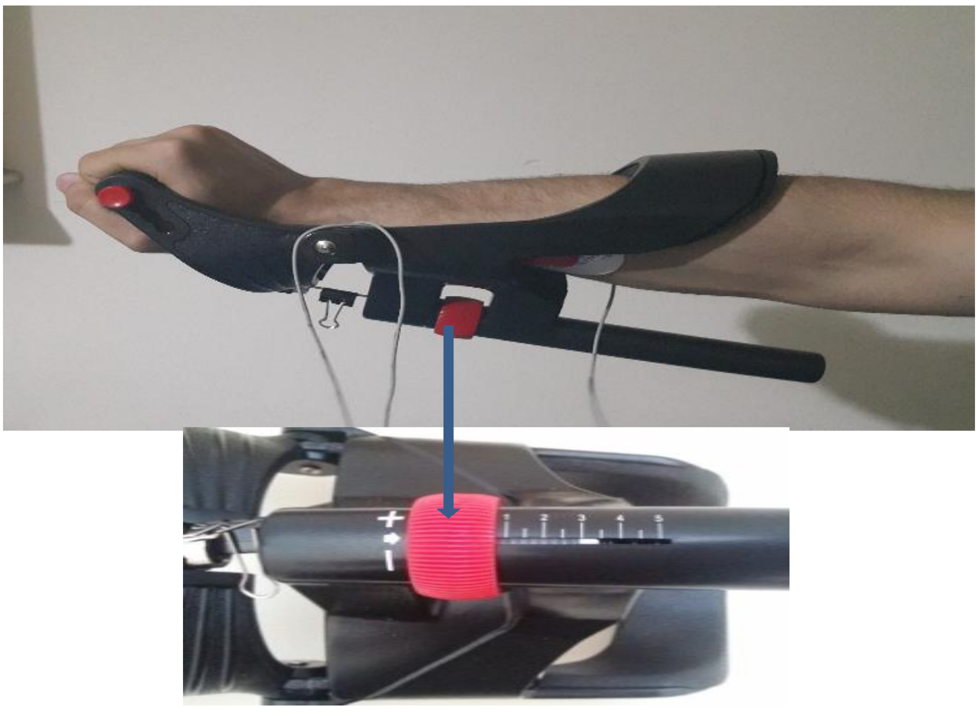


Figure 3.9 Wrist exerciser-extension

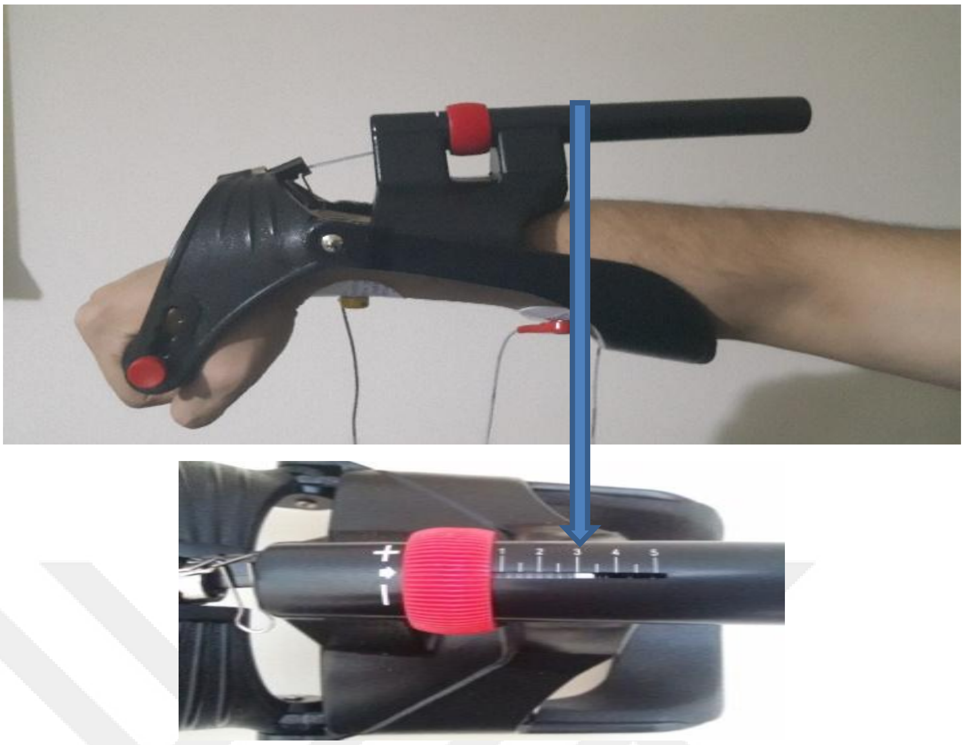
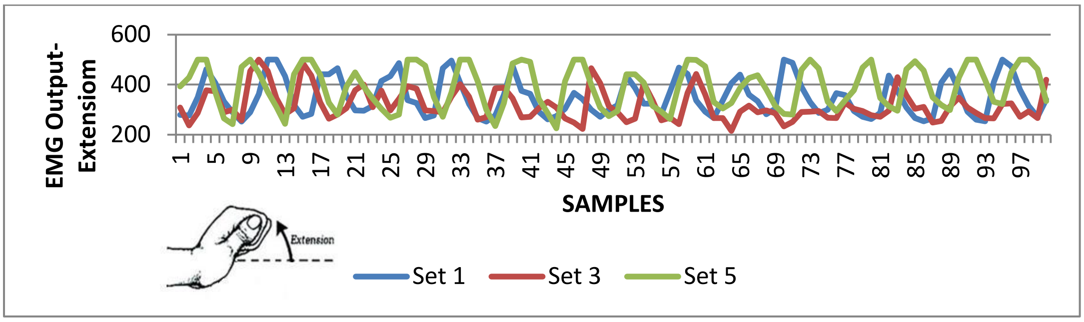


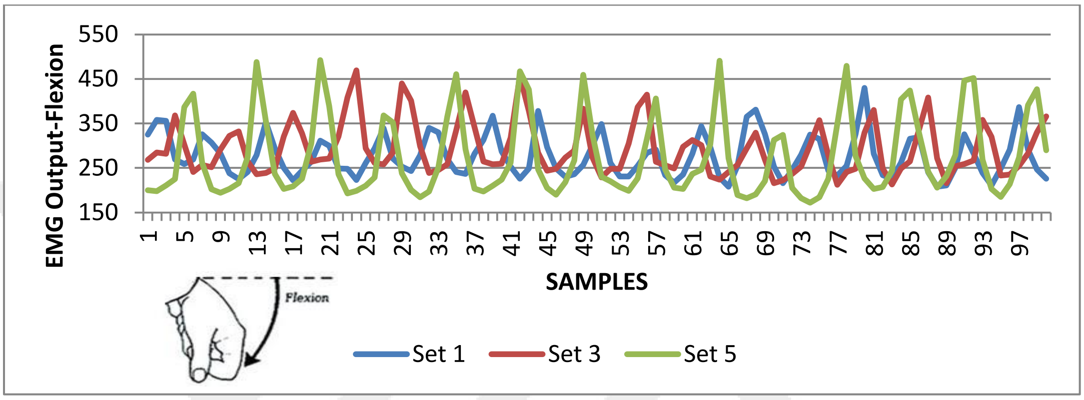
Figure 3.10 Wrist exerciser- flexion

Two subjects were chosen as project students (Gaziantep University-Mechanical Engineering Department). They were also volunteer healthy boys. EMG measurements are performed 3 (minimum 1-3- maximum 5) settings for flexion, 3 settings for extension, Measurements for Subject I are given in Figures 3.11 (a) and (b). Figures 3.11 (c) and (d) are given without wrist exerciser. The EMG signal frequency range is seen as 0-500 Hz. The dominant frequency range lies from 50-150 Hz with 1-10 mV. Figures 3.12(a) and (b) show the characteristics of flexion and extension. All measurements are taken in Mechatronics Laboratory; they were represented by a 5th order polynomial with high correlation coefficient as shown.

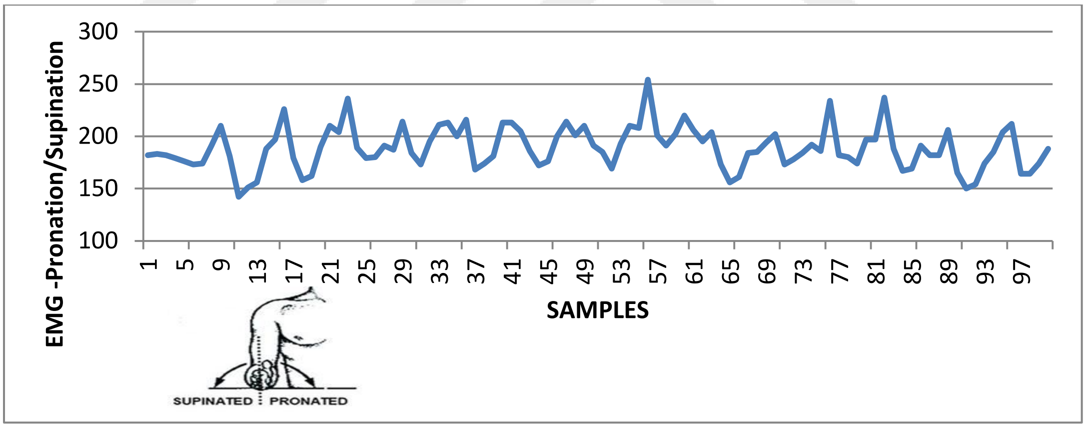
Subject I- *Male: Age=23, Weight=83 kg, Height=1.83 m*



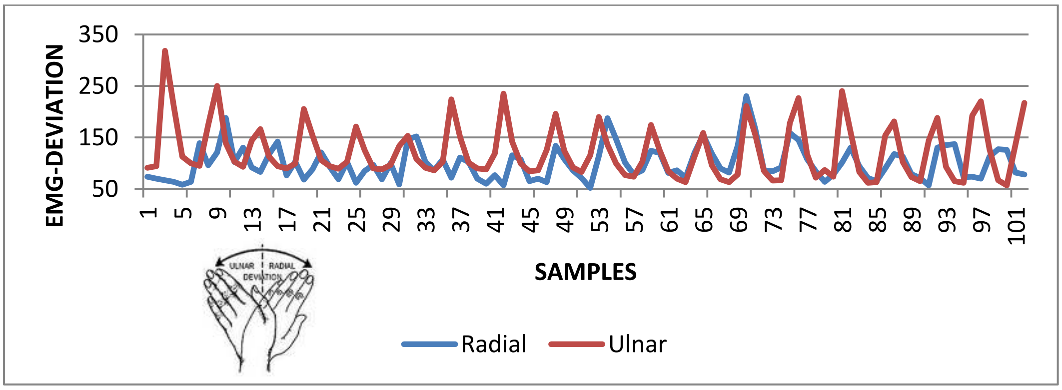
(a)



(b)

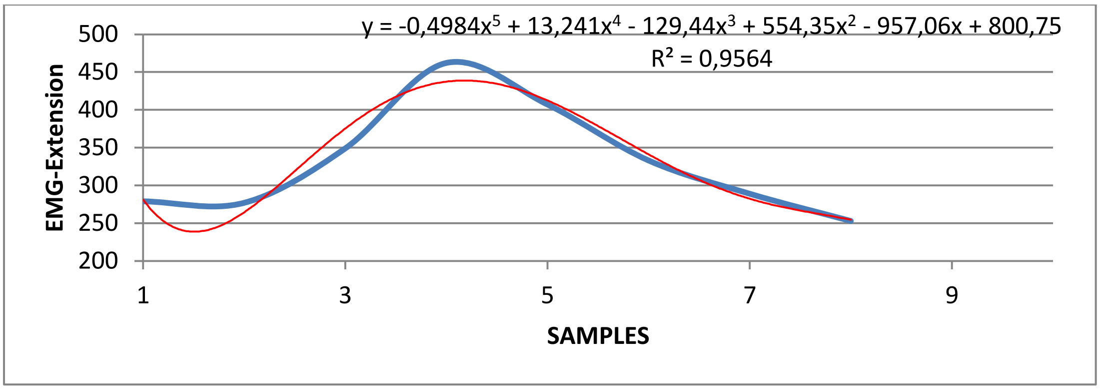


(c)

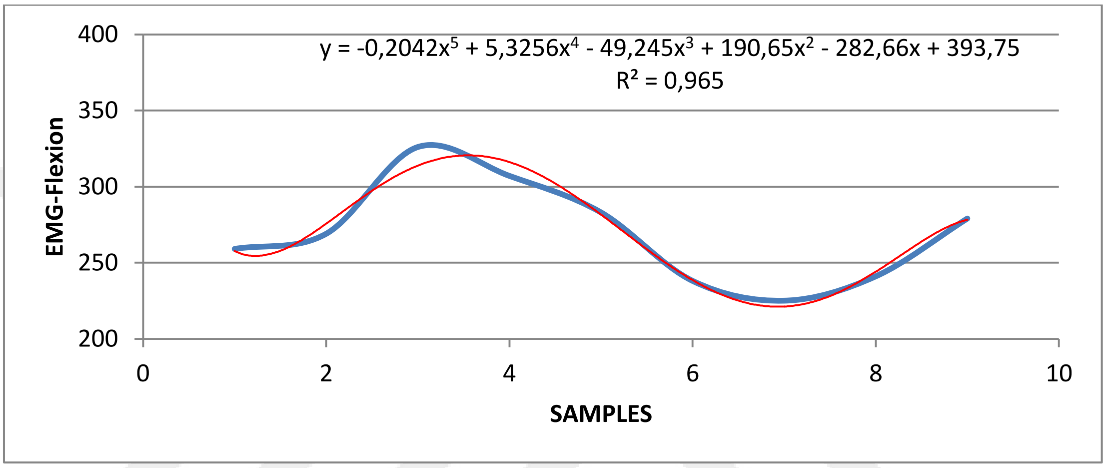


(d)

Figure 3.11 EMG measurements for Subject I



(a)

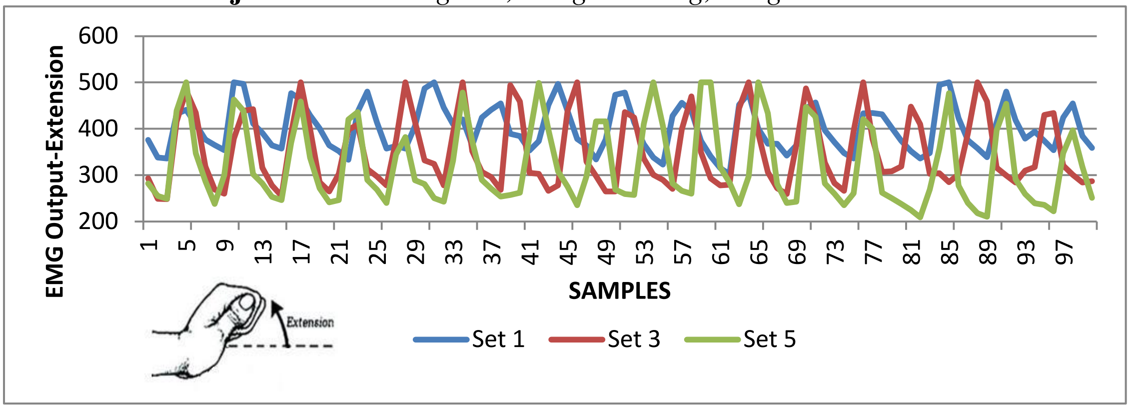


(b)

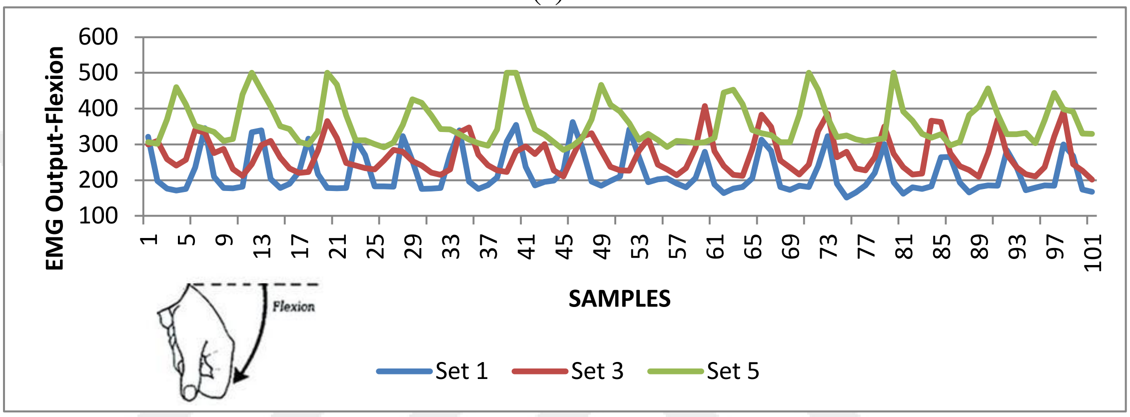
Figure 3.12 Extension-Flexion Characteristics –Subject I (Set 1)

Figure 3.12 (a) and (b) only show only one set condition (Set-I). A number of factors are noticed during measurement of sEMG. They can be studied as the timing and intensity of muscle contractions, the electrode and amplifier properties, the distance of the electrode from the active electrode for example. They all effect the bio signals taken. Characteristics of the EMG are given as 5th order polynomial as in extension and flexion. EMG output is represented by blue line: curved fitted is given in red line respectively. Characteristics of the signals are similar except the coefficients depending on the subjects muscle and the body strength. Figures 3.13 (a) and (b) show measurement for Subject II. Figures 3.13 (c) and (d) are given with exerciser.

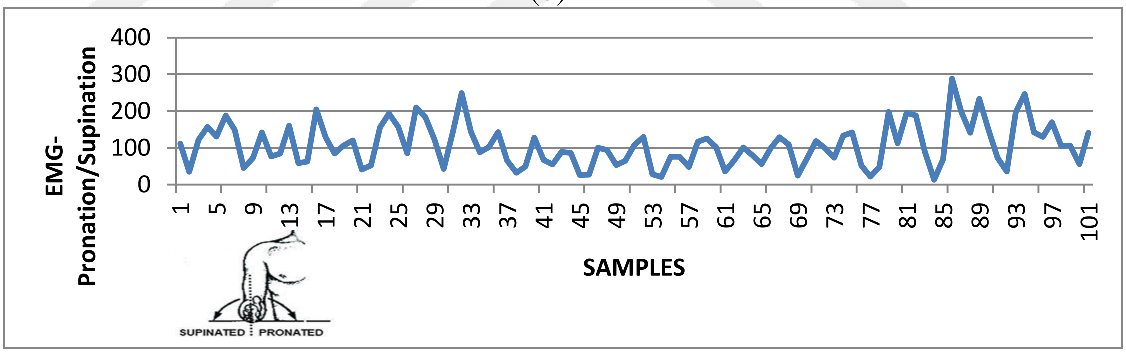
Subject II- *Male: Age 24, Weight=76 kg, Height=1.79 m*



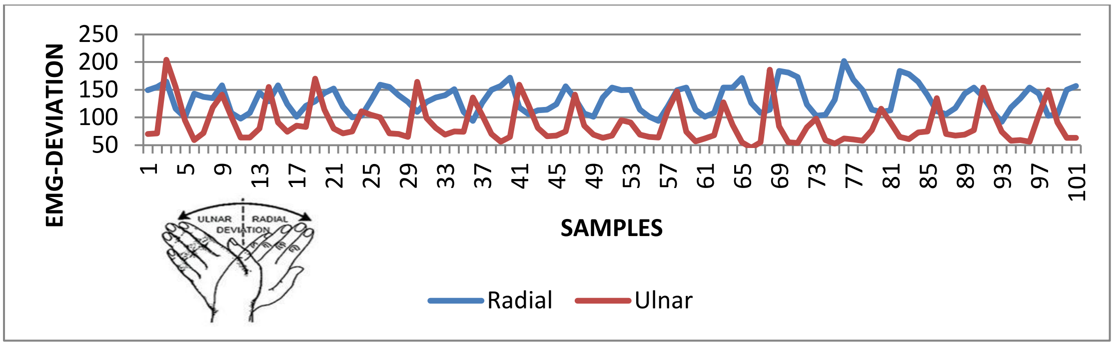
(a)



(b)



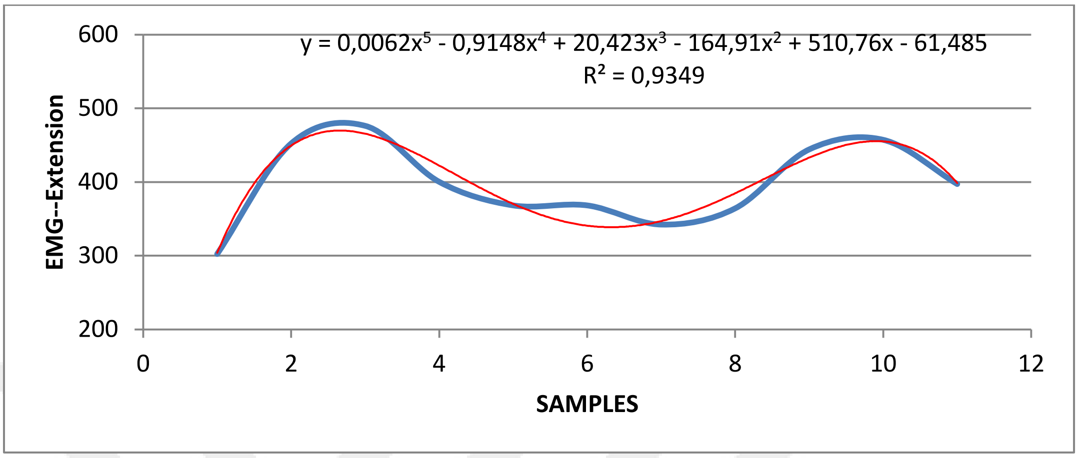
(c)



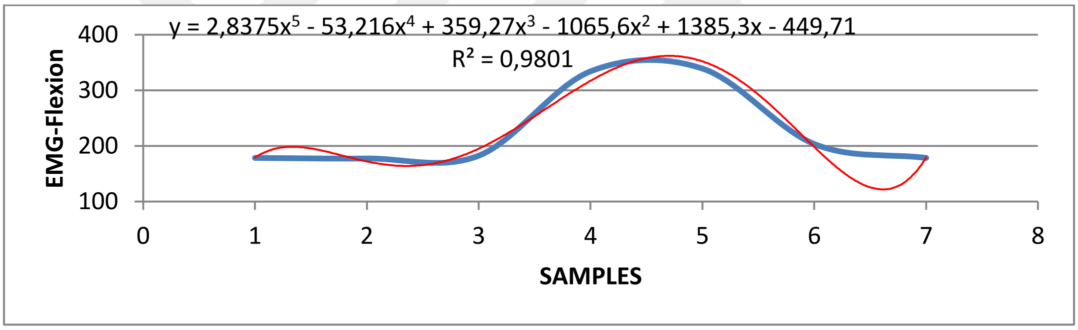
(d)

Figure 3.13 EMG measurements for Subject II

Subject II characteristics are studied. It was seen that it was giving a curve of 5th order. Similarly, this will be used whenever necessary for rehabilitation. Extension-Flexion characteristics are shown in Figure 3.14 (a) and (b).



(a)



(b)

Figure 3.14 Extension-Flexion characteristics –Subject II (Set 1)

CHAPTER 4

INERTIAL MEASUREMENT UNIT (IMU) EXPERIMENTAL SYSTEM SET UP

4.1 Introduction

This chapter describes the basic working principles of the XSens MTw system. XSens MTw Awinda and The Wrist Exerciser are used together. An inertial sensor is fixed to wrist exerciser to obtain information during wrist rehabilitation. We focused on flexion/extension motion first in the study. Then a passive exoskeleton is used with IMU for all motions available for the wrist rehabilitation. Measurements are given for further comparisons of their practical use herein.

4.2 Description of IMU System

Inertial Measurement Unit (IMU) sensors are seen in different applications in which most of them were in bio medical cases. The 3D orientation accuracy of inetial/magnetic sensors, their use in trunk inclination, hand writing motion tracking was seen in different studies [40-44].

XSens MTw system is used in this research as a part of a project. The MTw™ is a miniature wireless inertial measurement unit composed of 3D accelerometers, 3D gyroscopes, magnetometers and a pressure sensor. There is an embedded processor which can handle sampling, buffering, calibration and strap down integration (SDI) of the inertial data. It is responsible from the wireless network protocol for data transmission. It is combined with the MT Software Suite. The XSens Kalman Filter is available in the software for human motion (XKF3hm). The MTw allows real-time 3D orientation where up to 20 wireless motion trackers can be used in a network. The data can be provided as calibrated 3D linear acceleration, angular velocity, (earth) magnetic field and pressure data. Fields of use are seen as biomechanics, rehabilitation, sports and, virtual reality, human machine interface for robotics and motion capture [45].

The wireless MTw has got different areas of applications. The motion tracking systems on the subjects, or patients of concern can be easily provided. The Awinda USB Dongle offers wireless capabilities as the Awinda Station. It controls the synchronized wireless data from all wirelessly connected to MTw's (data up to 32 ones). MTw's are inertial measurement units which comprise 3D accelerometers, 3D gyroscopes, 3D magnetometers and a barometer which are powered by a Li-Po battery lasting 6 hours. Data is captured at a sampling frequency of 1000 Hz. The coordinate system used is as a right handed Cartesian coordinate system in Figure 4.1 as:

Figure 4.1 Awinda USB dongle and motion tracker - Orientation coordinate system [45]

4.3 Awinda Software

The MTw Awinda development kit is always supplied with software; MT Manager and a software development kit. MT Manager is designed for visualizing motion and recording data successively. This gives quick and easy use of the MTw and Awinda Master in Figure 4.3. This is a portable system. The MT Software Development Kit (SDK) is provided with example codes which are in C#, C++ and MATLAB. This software is intended to make application development for the MTw easily accessible to use. MT manager screen is shown in Figure 4.2.

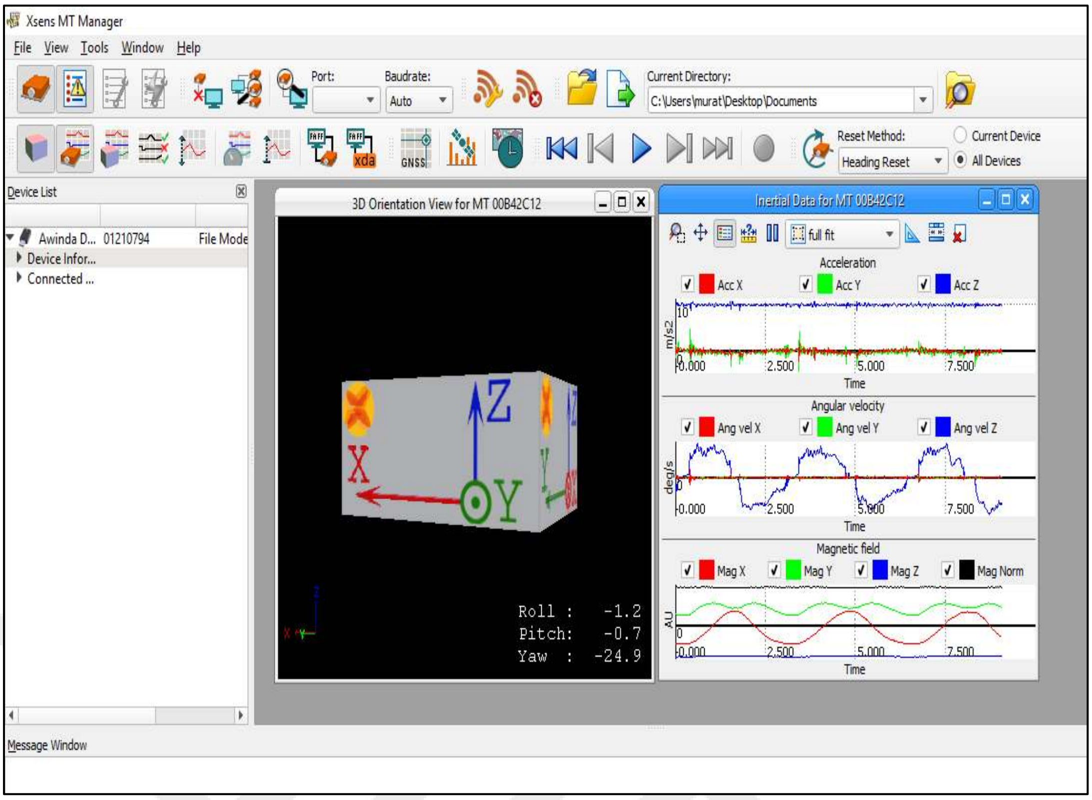


Figure 4.2 MT manager [46]

4.3.1 Heading Reset

When performing a heading reset, the new global reference frame is chosen. The global X-axis points in the direction of the sensor with the global Z-axis vertical (along gravity, pointing upwards). The new global frame has the Z axis along gravity, pointing upwards. The sensor X-axis is perpendicular to the global Z-axis and the Y-axis. A right handed coordinate system is formed in Figure 4.3. The orientation of the sensor is given by using Euler representation (three rotations as roll, pitch and yaw), Unit quaternion's and rotation matrix (3x3). Before recording the data, it is ensured that the correct directory is stated in 'File Control' menu. There is the red icon in the Recording and Playback to record data. Record button is also available in Playback and Record. When the icon depressed the data is recorded. When the user decides to stop recording, the same icon is clicked again. Data is then automatically saved in the directory specified by the user. File name changes depending on how many subjects are being tested. The users depress the record button until all data is downloaded from the IMU for further use.

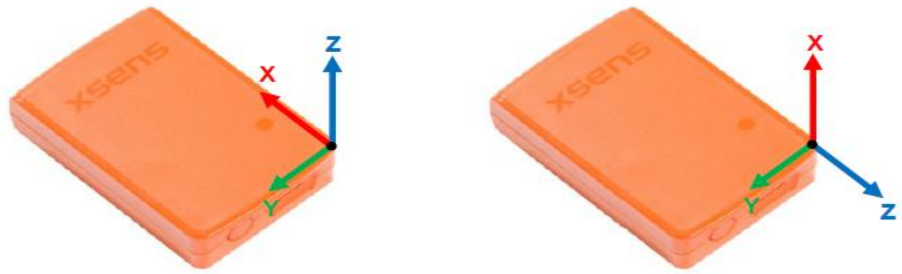


Figure 4.3 Heading reset description

4.3.2 Saving and Exporting IMU Data

MT Manager allows replaying MTB files. To utilize the data in MT Manager, the MTB file should be made ready. The data is selected to see what happens to the desired data. Data is easily seen using the 3D orientation box, sometimes different graphs are used; as inertial, orientation, pressure etc.). Playback and Recording menu is active when the "*Play*" icon is selected. While the file is recorded, green light is on to show the progress is active on the left-side of the screen. MTB files can be exported to ASCII format. Specifications of IMU system are given in Table 4.1.

Table 4.1 Specifications of IMU [47]

Communication			
Range	Awinda station	Awinda dongle	
Open space	Up to 50 m (165 ft.)	Up to 20 m (65 ft.)	
Office space	Up to 20 m (65 ft.)	Up to 10 m (33 ft.)	
Wireless protocol	Xsens patented Awinda protocol [1]		
Receiver	Awinda Station / Awinda Dongle		
Orientation			
Static Accuracy (Roll/Pitch)	0.5 deg RMS		
Static Accuracy (Heading)	1 deg RMS		
Dynamic Accuracy (Roll/Pitch)	0.75 deg RMS		
Dynamic Accuracy (Heading)	1.5 deg RMS		
Tracker components			
Dimensions	3 axes	3 axes	3 axes
Full scale	± 2000 deg/s	± 160 m/s2	± 1.9 Gauss
Tracker placement	Easy fastening with Velcro straps		
Internal sampling rate	1000 Hz		
Latency	30 ms		
Buffer time (retransmissions)	10 s		
Battery life (continuous use)	6 Hours		
Dimensions Tracker	47 x 30 x 13 mm (1.85 x 1.18 x 0.51 in)		
Weight	16 g (0.56 oz.)		
Operating temperature range	0°C – 50°C		
Wireless update rates			
1 MTw	120 Hz		
5 MTw	120 Hz		
9 MTw	100 Hz		
10 MTw	80 Hz		
20 MTw (maximum)	60 Hz		

4.4 XSENS Data for Subject using Wrist Exerciser

A write and forearm trainer is introduced as the Wrist Exerciser. The exerciser provides changing resistance to the user during exercises. It's designed as forearm support keeping the wrist at the right position. There is a soft handgrip allowing adjustable positions depending on users hand size. One volunteer (healthy subject) is chosen for the test using wrist exerciser with IMU. (Volunteer1-Male: Age=23, Weight=98 kg, Height=1.91m) Measurements are performed at Gaziantep University, Mechanical Eng. Dept., Mechatronics Laboratory (May 2018). Experimental system is given in Figure 4.4 (a) and (b) as positions of F/E. Orientation Data for Flexion/Extension are given in Figures 4.5 with Orientation view.

(a) (b)

Figure 4.4 Wrist Exerciser - IMU measurement

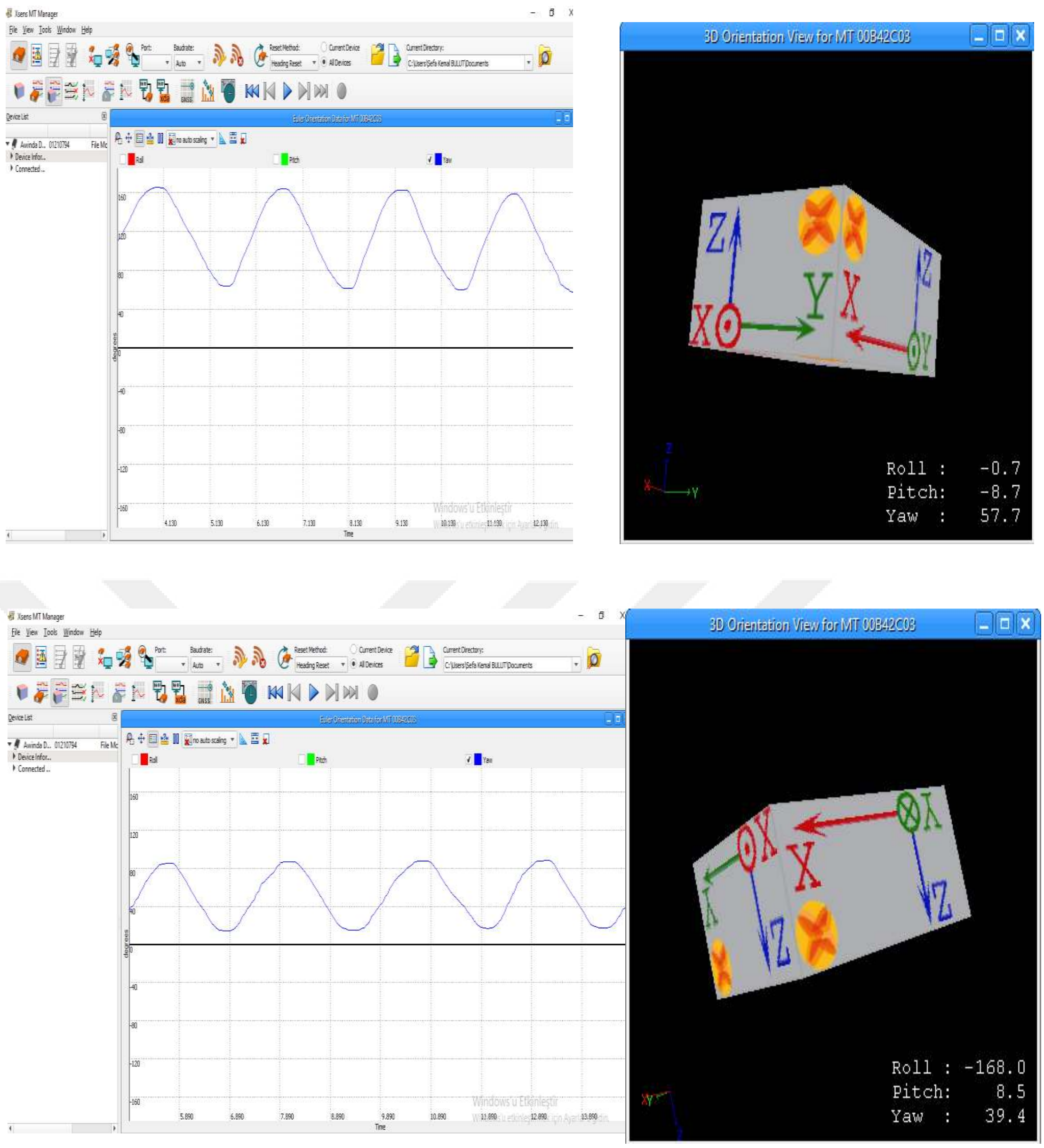


Figure 4.5 Orientation data for flexion - 3D orientation view for flexion

Figure 4.6 shows extension motion with IMU using Wrist Exerciser. A healthy volunteer (in Figure 4.4) data is given here in laboratory. Extension movements are recorded for many cycles. Here 4 motion cycles are given. Extension motions shown in 2 seconds performing nearly 70 degrees.

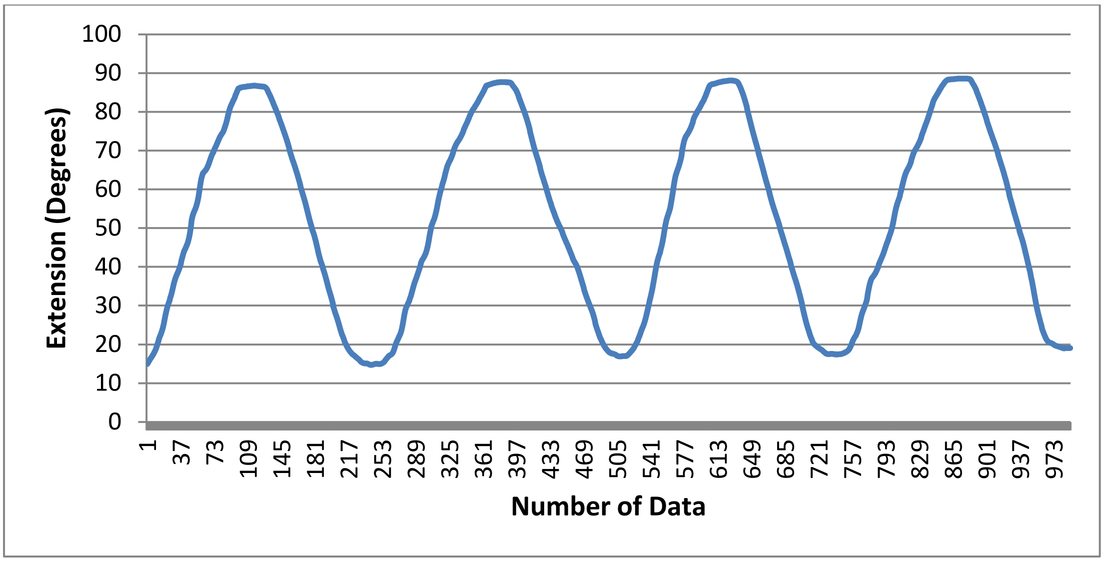


Figure 4.6 Extension movements with IMU

4.5 Description of Exoskeleton Movement with IMU

M.E. Kütük et al [48] have designed an exoskeleton assisted by robot for passive wrist and for forearm and wrist rehabilitation in a previous project. Module consists of three revolute joints at the wrist such that it corresponds to wrist Pronation/Supination (PS), Flexion/Extension (FE) and Abduction/Adduction (AA) movements. Wireless motion tracking is performed by IMUs available afterwards.

Figure 4.7 Wrist exoskeleton modules [48]

A preliminary design is given the different physical characteristics of each patient; it is normal and necessary for the orbits of the robots to vary according to the disease. In the first step, the robot action must be taught robotic through the haptic device. The trajectory planning algorithm to be implemented will reconstruct this movement with the feedback signals coming from the patient and the boundary conditions to be determined, so as to be faithful to the general characteristic of the movement. As a different case study, it is desired to make passive movements directly to the patient by controlling the six degree of freedom serial robot simultaneously with the haptic device [48]. A wrist rehabilitation module is designed as an exoskeleton mechanism in a different project in Figure 4.7. Module has got three revolute joints at the wrist in which it can provide pronation/supination (PS), flexion/extension (FE) and abduction/adduction (AA) movements. A volunteer 24 age healthy male is seen in Figures 4.8 to 4.10 IMU fit with the exoskeleton. Figure 4.11 shows the data recorded for allowable motions successively.

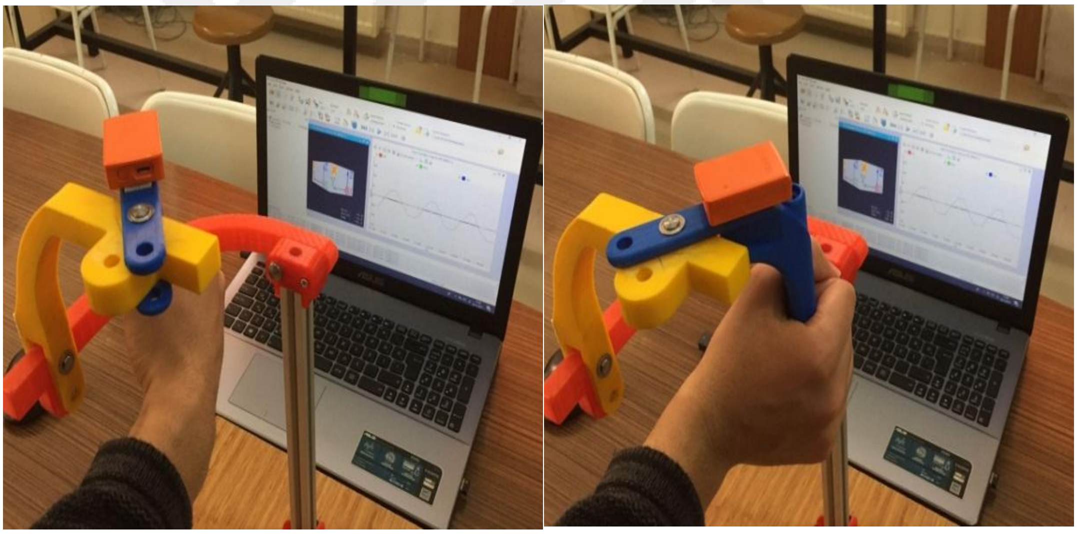


Figure 4.8 Abduction/Adduction motions and data analysis with MTw Awinda

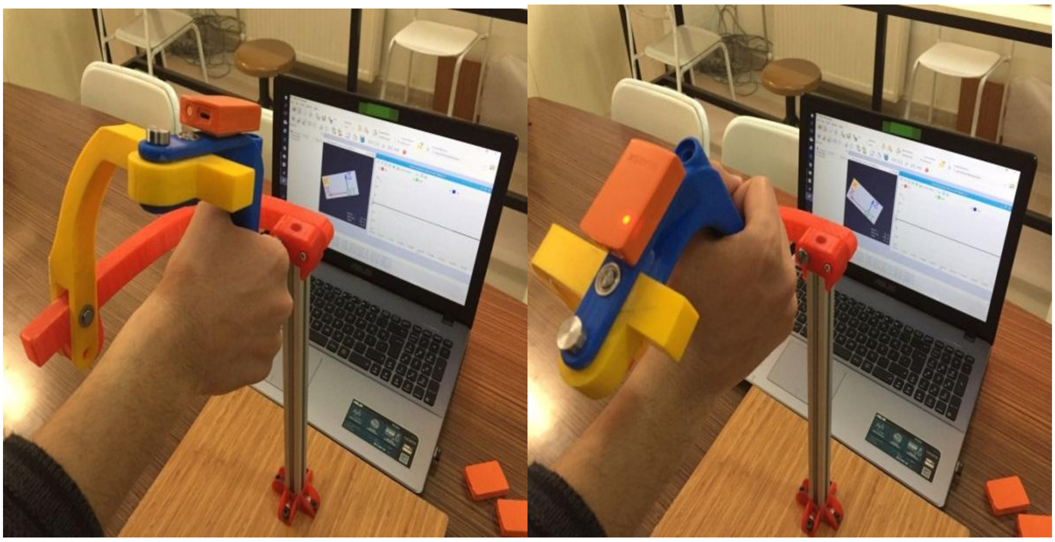


Figure 4.9 Flexion/Extension motions and data analysis with MTw Awinda

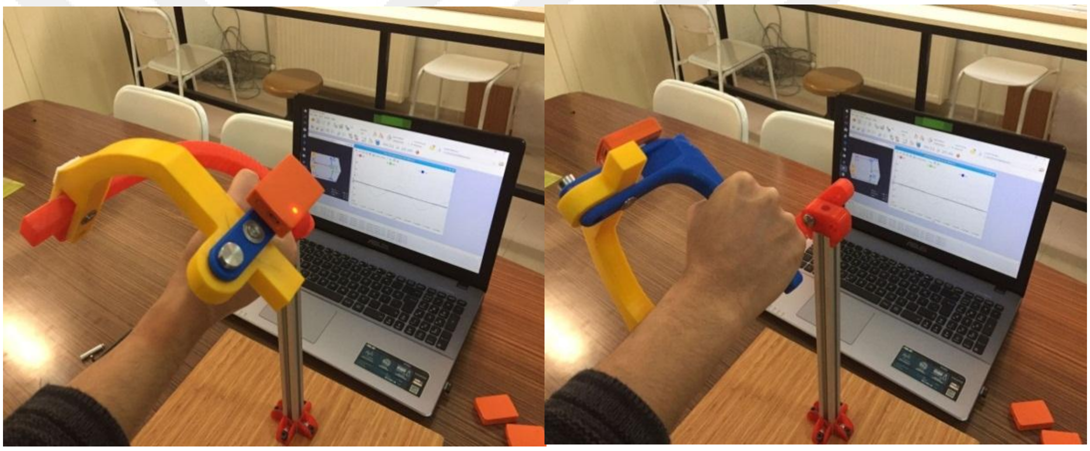
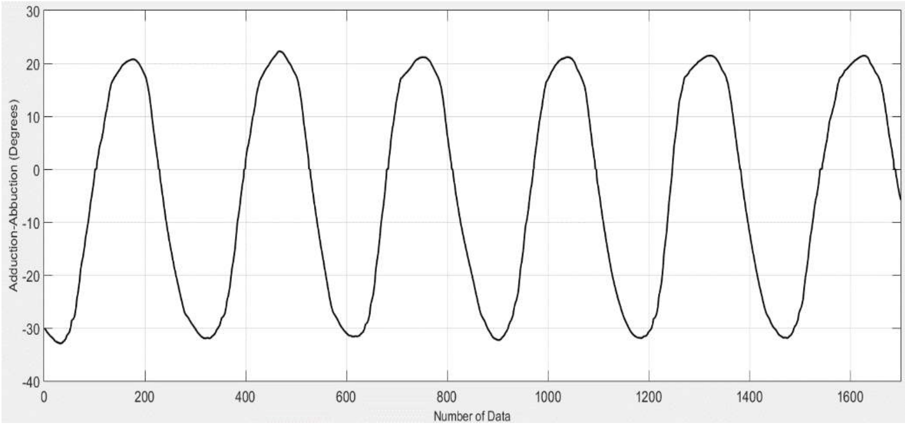
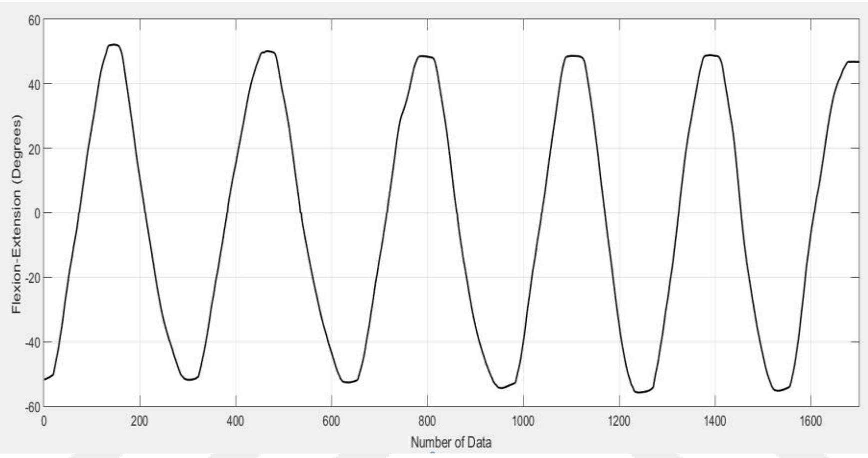


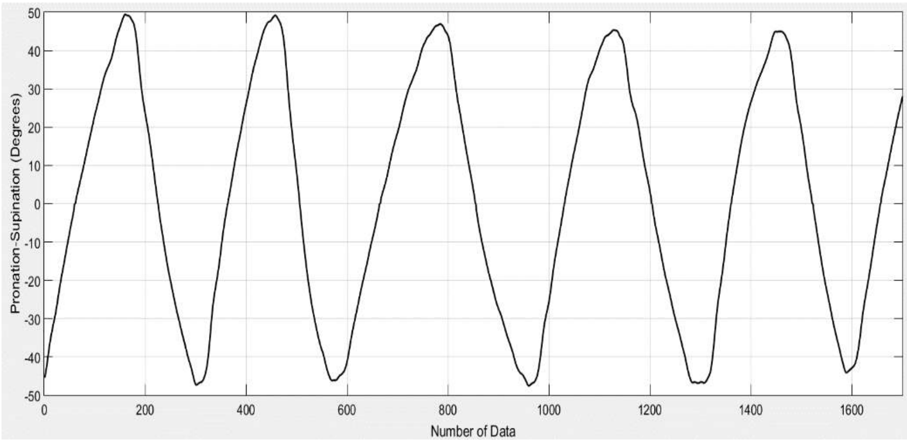
Figure 4.10 Pronation/Supination motions and data analysis with MTw Awinda



(a) AA Motion



(b) FE Motion



(c) PS Motion

Figure 4.11 Results with MTw Awinda

CHAPTER 5

CONCLUSIONS

5.1 Discussions

Electromyography (EMG) is obtained by contracting muscle to produce an activation. Surface EMG has been widely used to detect human movement. Muscle contraction and relaxation causes EMG signal. Signals are taken, evaluated and then utilized in different applications on biomedical use. EMG based robotic systems have been designed as hand prostheses, upper-lower prostheses, hand exoskeletons, upper-lower exoskeletons. Its use in prosthesis is seen to be very effective.

To perform rehabilitation initially wrist anatomy and motion analysis are studied by considering movements and limitations of a human wrist. Use of sEMG and IMU data was searched and findings and limitations are included. Muscles relating the wrist were reviewed in Chapter 2. EMG signals and experimental recording system were explained in Chapter 3 with EMG signal characteristics. An alternative system with IMU's was described in Chapter 4. Finally all recordings and results taken were compared and utilized to be a guide for bio signal use in rehabilitation.

i) Remarks for EMG Measurement

Disposable surface EMG (sEMG) electrodes were used during sEMG recording. Healthy volunteers were tested system using EMG sensor as a part of a project. An experimental system was built; measurements were recorded and presented to be utilized later. Wrist exerciser is bought to perform basic exercises to provide a standard base comparison later on. During studies it was seen that EMG signals could be detected by using simple electrodes but it was very difficult to decompose, process and then classify. There was a need to acquire advanced methods. Thus some recordings were presented herein with mathematical characteristics. They were studied mathematically in the case of Flexion/Extension and Abduction/Adduction since they are accepted movements in wrists. Pronation/Supination movements were studied, but they were generally included in forearm motion. They were not utilized on the exoskeleton designed. This study is provided a base for a research study which is continuing in Gaziantep University, Mechanical Engineering Dept,, Mechatronics Laboratory an exoskeleton design in which to be activated by an industrial robot (Denso).

ii) Remarks for IMU's

Having seen some difficulties during sEMG measurement, IMU's were considered as alternative for taking bio signals. IMU measurements were taken by using wrist exerciser and exoskeleton designed in Gaziantep University, as a part of Ph. D study. Two subjects were used during measurements. They were included in Chapter 4. Since IMU system (XSens) was used with a software, it was easy to store and classify data. Better results were obtained during measurement. These results were then utilized when the exoskeleton to be integrated with robotic arm. It will then provide robotic assisted rehabilitation.

iii) Remarks for EMG and IMUs Together

A set of experiments were carried out EMG and IMU with wrist exerciser by Ms. Students at the same time. It was seen that there was no difference in settings either setting 1, 3 or 5. IMU was given the same results. No coordination was mathematically studied in detail. However IMU's were not given problem in muscle separately. EMG systems could reveal this information indeed. This was noticed while performing tests.

iv) EMG and IMU's use in Wrist Rehabilitation

Finally a decision was made for IMU systems. Three IMU's were bought. One of them was enough to carry out measurements for the exoskeleton. Studies were not completed. Later it can be used in clinical sense having taken ethics permission as rehabilitation alternative. The point to be done next will be robot assisted rehabilitation in Mechatronics Laboratory.

5.2 Recommendations for Future Study

The findings in this study will provide an important reference for use of EMG based systems and IMU measurements rehabilitation purposes. There are some points which are not detailed because of time limitation. At the beginning of this thesis study, a background was necessary about rehabilitation alternatives in Gaziantep. Government hospitals and Private Hospitals were search on utilities available for rehabilitation especially for the wrist. The position seen was all rehabilitation was performed by stuff in related departments. Basic devices were available. Thus a decision was made to reveal this for future assisted rehabilitation in professional sense.

(i) To utilize EMG systems properly, Arduino-EMG sensor for basic use was not enough. A medical EMG measurement system will be needed. Specific patterns can be later recognized by a 'healthy' subject.

(ii) IMU-based motion capture systems can be utilized for various exercises. Specific patterns can be later recognized by a 'healthy' subject forming a basis for the comparison and assessment of patients. They can be simply utilized for standard rehabilitation.

(iii) Biomedical signal processing can be studied using real-time monitoring. Biomedical signals are acquired by monitoring for diagnosis. Fourier transform can be used for frequency analysis of time domain signal. Various methods were seen in background studies. Pathological conditions are detected by the magnetic resonance imaging for examples of traumatic and neurologic cases. However, signals were utilized in time domain using sample number. Experimental studies were taken too much time especially EMG measurements. This is left as future study. Signals can be utilized with help of a package like Matlab ®.

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APPENDIX

US005454769A

United States Patent [19]
Chen

[11] Patent Number: 5,454,769
[45] Date of Patent: Oct. 3, 1995

[54] WRIST AND FOREARM EXERCISE APPARATUS WITH IMPROVED RESISTANCE ADJUSTMENT DEVICE

[76] Inventor: Ping Chen, No. 20, Nan-Mei St., Taichung City, Taiwan

[21] Appl. No.: 401,628

[22] Filed: Mar. 9, 1995

[51] Int. Cl.[6] A63B 5/00

[52] U.S. Cl. 482/46; 482/124; 482/128; 482/908

[58] Field of Search 482/44, 46, 49, 482/45, 124, 128, 908, 121, 122, 131, 133, 134

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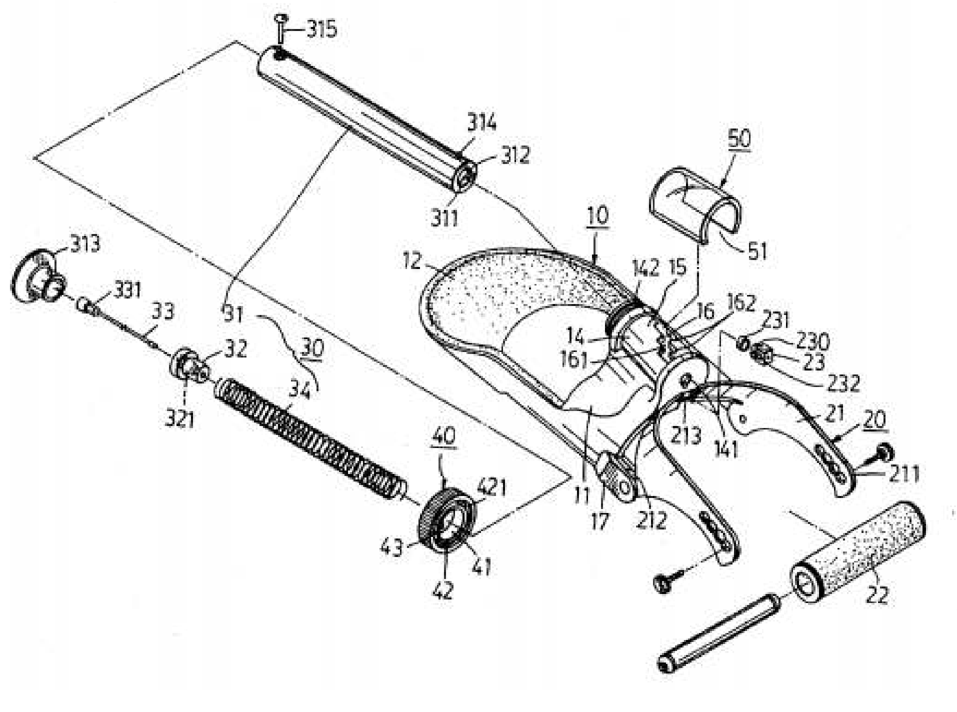
Primary Examiner—Stephen R. Crow
Attorney, Agent, or Firm—Ladas & Parry

[57] ABSTRACT

A wrist and forearm exercise apparatus includes a forearm support unit for extension of a forearm of a user therethrough, a grip assembly mounted swingably on the forearm support unit for gripping by a hand of the user, and a resistance adjustment device. The forearm support unit includes a tubular body having a peripheral wall with an intermediate portion formed with a stepped groove. The stepped groove includes several L-shaped sections, each of which has an axial portion and a radial portion. A coiled compression spring is accommodated within an adjustment tube which has a front end portion mounted slidably within the tubular body. A radial pin is fixed on the adjustment tube and engages the stepped groove. Movement and rotation of the adjustment tube relative to the tubular body moves the pin in the stepped groove so as to change the compressed extent of the spring, thereby adjusting the resistance to the swinging movement of the grip assembly on the forearm support unit.

3 Claims, 6 Drawing Sheets



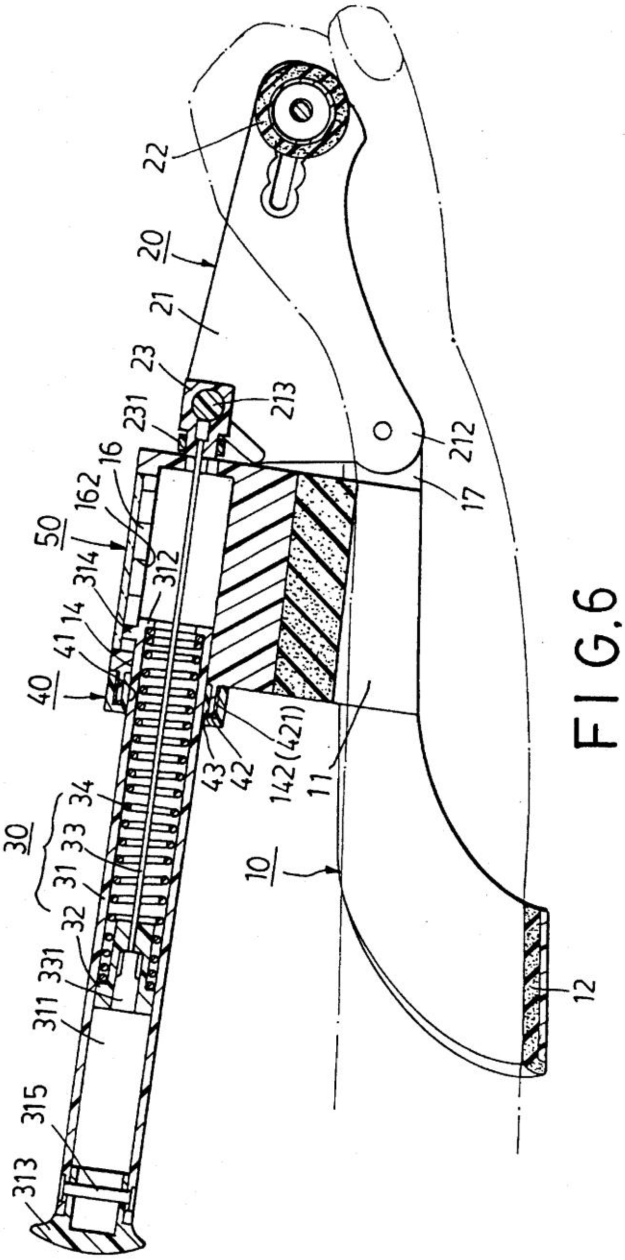

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FIG.6

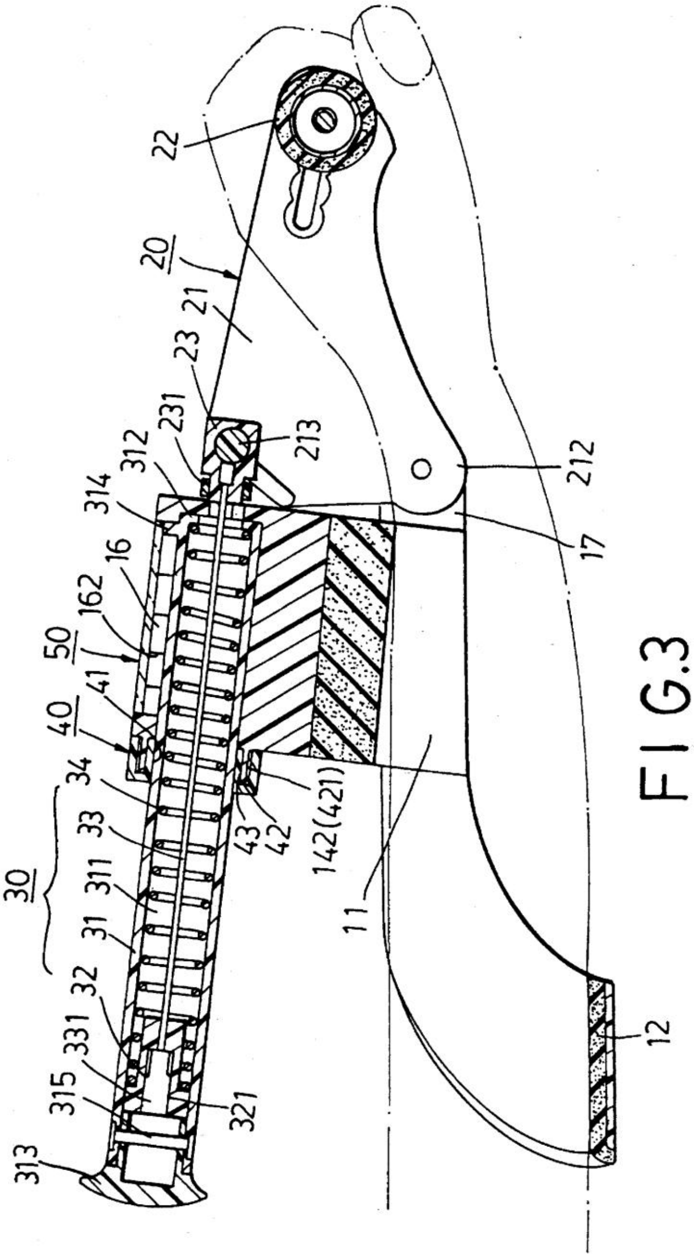
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FIG.3

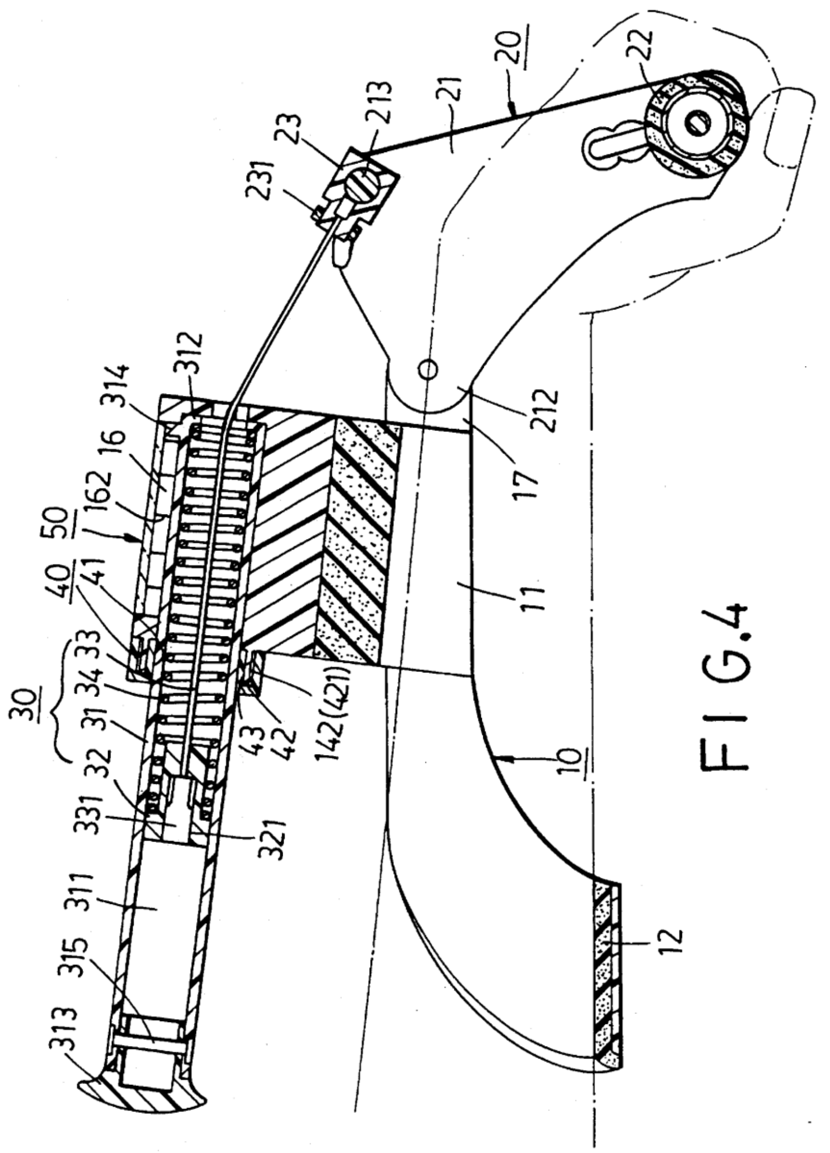
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FIG.4